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AN EXPERT SYSTEM SOLUTION FOR THE QUANTITATIVE CONDITION ASSESSMENT OF ELECTRICAL DISTRIBUTION SYSTEMS IN THE UNITED STATES AIR FORCE

THESIS

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AFIT/GEM/DEM/91S-10

The views expressed in this thesis are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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THESIS

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David O. Paine

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Abstract

Faced with a rapidly decreasing budget, the Air Force is in need of a method to objectively evaluate its aging utility infrastructure assets. This objective evaluation could be used to compare similar facility infrastructure systems for identification of possible problem areas and prioritization of major repair projects.

This thesis developed a component model which can be used to objectively evaluate a typical electrical distribution system. The Delphi process was used to gather expert opinions regarding three areas: (1) the critical components which should be included in the model, (2) the relative importance of each selected critical component, and (3) the criteria used to evaluate each of the selected critical components. The model is used to assign a numerical rating ranging from 0 to 100 to each critical component. The condition indices for the critical components are then combined using a relative weighting scheme to arrive at the overall electrical distribution system condition index.

The component model was encoded into a computer based expert system shell to provide a smooth user interface and easy update capabilities. The resulting expert system determines component and system condition indices based on user input or available database information.

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I. Introduction

General Issue

Many of the Air Force's facility infrastructure (F/I) assets have aged to the point where rapid deterioration may lead to catastrophic failure (18). Facility infrastructure assets include structures and utility systems which are intended to support the mission of an entire base (40:1). Examples of F/I systems include: electrical distribution, water distribution, natural gas distribution, steam production and distribution, liquid fuel storage and distribution, fire protection, and roadway network. Many of the F/I systems support mission critical operations. Failure of any of these systems would result in drastic losses associated with production and support to critical national defense assets (4). A possible catastrophe of this nature may be avoided through increased levels of maintenance and repair. However, recent budget cuts have severely limited the funds available for facility infrastructure projects.

Even though we continue to face declining budgets, Major General Ahearn, Director of Engineering and Services, HQ/USAF, states we are still being asked to "develop, maintain, and operate an aging infrastructure" (1:1). In order to ensure the reliability of F/I assets

now and in the future, objective assessment methods for the various F/I systems must be developed and used to properly allocate limited funds to those systems in greatest need of repair.

Specific Problem

At present, the Air Force has no method to objectively quantify the current condition of facility infrastructure assets. The standard condition assessment method in use today embodies a qualitative self-assessment program through which each base rates its F/I systems as good, fair, or poor. These ratings are then used by base level project programmers as justification when submitting F/I projects for higher headquarters approval (4; 15).

According to Mr. Tom Cadogan, Chief of the Maintenance Engineering Division at Headquarters, Air Force Logistics Command:

> It is difficult to support facility infrastructure projects at the headquarters level when they are justified by base level programmers on a solely subjective basis, often without consultation between key engineers and key technicians who are jointly responsible for the system (4).

Mr. Cadogan further states that his main interest is to see the Air Force develop a standard condition assessment model which could be used by any engineer knowledgeable in the subject area to get the same results. Objective reviews from engineers instead of subjective reviews from programmers are needed to establish realistic command-wide project priorities (4).

Due to the many differences associated with each F/I system, it would be difficult to develop a single quantitative model to encompass all such systems. Therefore, a separate model must be developed for each facility infrastructure asset (40:2).

Research Objective

The purpose of this research is to develop a critical component model of an electrical distribution system and to encode this model into a computer based expert system which can be used at each base to provide a quantitative condition assessment of that base's electrical distribution system.

Investigative Questions

To meet the research objective, the following investigative questions were answered:

1) What are the critical components and/or critical system factors which most affect the condition of the electrical distribution system?

2) Can the critical components be further broken down into subsystems and evaluated in terms of those subsystems?

3) What characteristics of each component, subsystem, or system factor can be used to describe its condition?

4) How much weight should each subsystem or subfactor have in determining the condition of its related critical component or factor?

5) How much weight should each critical component or system factor have in determining the overall system condition?

6) Can expert system technology provide a suitable interface between a system engineer and the model developed in questions one through five? If so,

7) Which expert system shell will best fit within the constraints of this particular problem?

Scope and Limitations of Study

For the most part, electrical distribution systems are similar throughout the Air Force. The systems may be arranged differently (i.e. ring distribution vs. radial distribution), but the basic components

remain the same from system to system (30). The primary differences lie in where and how the electrical power is generated as well as where and how the electrical power is used. Figure 1 shows a one-line diagram of a typical radial distribution system.

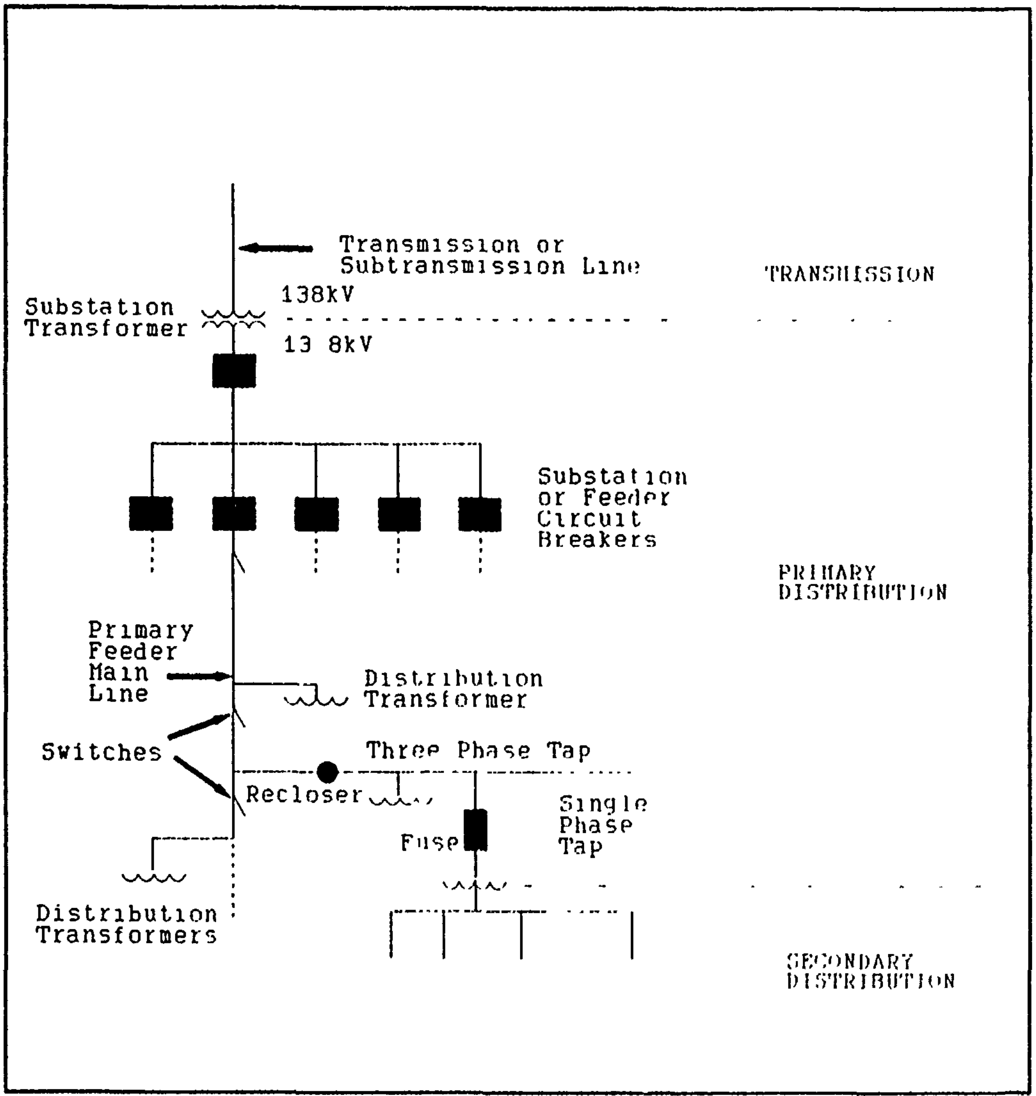

Figure 1. A Typical Electrical Distribution System

This study will not address power generation and transmission, nor will it address power distribution within individual buildings. This study will encompass the primary electrical power distribution system from the point immediately after power is generated (if power is generated on the base) or from the point where primary power cables first enter the confines of the base (if commercial power is used) and will continue to the point immediately after the final voltage transformation has occurred on each branch circuit.

Definition of Key Terms

Several key terms should be defined to allow a more thorough understanding of the work which follows.

Electrical Distribution System: A network of components used to transport, route, and transform electrical power from its point of generation to its final point of use. Included in the distribution system components are:

1) Transformers - used to transform electrical power from high voltages used for power distribution to lower voltages needed for most applications.

2) Substations - a centrally located facility containing several subsystems used in switching and routing electrical power.

3) High-Voltage Power Cables - Used in transporting electrical power throughout the electrical distribution system.

Subsystem: A major division or function of the electrical distribution system which can be considered an individual system by itself (40:80). Examples of subsystems could include power transformation, substations, and high-voltage cable networks.

Critical Component: Individual parts or pieces of equipment which are contained within various subsystems and which are necessary for the

proper operation of that subsystem (40:80). Examples could include individual transformers, primary switchgear, and high-voltage cables and connections.

System Factor: A non-physical attribute of an electrical distribution system which has an effect on the operability, maintainability, and overall condition of that system. Examples could include system integration and system maintenance history.

Critical Subfactors: Individual factors or attributes which impact, and can be used as a measure of, system factors. Examples could include coordination studies, system capacity, maintenance plans, and outage records.

Weighting Factor: A number between 1 and 10 (inclusive) used to indicate the relative importance a particular subsystem, component, or factor has in regard to other subsystems, components, or system factors within the electrical distribution system (40:80). A highly critical subsystem, system factor, or component will receive a higher number than a less critical one.

Evaluation Criteria: Methods and/or rules which can be used while inspecting critical components to determine their condition or evaluating system factors/subfactors to determine their impact on system operation. Criteria could range from simple visual inspection results to more complicated analysis which include equations or simple models. In all cases, the criteria must be specific and the methods required for accomplishing the evaluation should be within the capabilities of the base squadron (40:80-81).

Condition Assessment: An evaluation, either quantitative or qualitative, of the capabilities of the subject system to perform as originally designed. For this study, condition is further defined as the ability of that system to continue to provide the necessary service needed for the base to meet both current and future mission requirements. Condition includes the physical condition of individual components (physical attributes and characteristics) as well as non-physical factors such as capacity of the system and maintenance history.

Condition Index (CI): A numerical, scaled rating assigned to the overall system as a result of a qualitative condition assessment. The condition index is based on individual component, subsystem, and factor conditions and their relative weights within the total system. The CI number provided in the assessment can be used to accurately rate one system against another.

Expert System: A computer program which is designed to model the thinking and problem solving capabilities of a human expert in his or her field of expertise (28:1). The individuals who possess the expertise are referred to as the domain experts (11:Sec 1,2).

Overview of Chapters

This chapter discussed the need for a quantitative rating system for use in evaluating facility infrastructure assets. In particular, it proposed the development of a component model for use in quantifying the condition of a typical electrical distribution system and encoding the model into a computer based expert system.

Chapter II reviews current literature dealing with attempts to apply component modelling to develop a quantitative rating system for

electrical distribution systems. It also gives a general overview of expert systems and how they apply to this research.

Chapter III discusses the knowledge acquisition process as it relates to expert system development. The principal avenue of knowledge acquisition uses the Delphi technique to achieve a "collective" knowledge base through interviews and surveys conducted on a panel of 15 experts. Therefore, the Delphi technique is also discussed in this chapter.

Chapter IV introduces the component model developed for use in assessing a typical electrical distribution system. Chapter V describes the expert system developed from the component model. Finally, Chapter VI documents recommendations for use of the expert system as well as recommendations for further research.

II. Literature Review

Overview

Chapter I of this proposal established the need for a method to quantitatively assess the condition of facility infrastructure (F/I) assets throughout the Air Force. The focus of this chapter is to review available literature which applies to the general area of quantitative condition assessment of F/I assets and to evaluate information which applies to the specific research objective, developing a computer based expert system for condition assessment of electrical distribution systems in the Air Force.

The chapter is divided into three sections; evaluation of available rating schemes for electrical distribution systems, critical component modelling techniques, and expert system applications. A thorough search of the Defense Technical Information Center (DTIC) and DIALOG data bases failed to uncover any published works on electrical distribution system condition assessment. Consequently, this review looks at material regarding current efforts in this area as well as research studies covering similar areas.

Rating Schemes

Rating schemes for F/I systems have been developed by both government agencies and private industry. This section summarizes those studies, completed or underway, which impact this research.

U.S. Air Force. In 1988, Headquarters Air Force Logistics Command implemented a Facility Infrastructure Process Action Team

(FIPAT). The primary goal of the FIPAT was to "improve facility infrastructure (F/I) planning and requirements identification" (40:7-8). After identifying 17 major F/I systems, including electrical distribution, the FIPAT visited several of AFLC's larger bases and interviewed local experts on F/I critical system components. The experts were asked to identify the critical components within each system and to give their opinions on the relative weights of each critical component with respect to other critical components (19:7) According to Mr. Tom Cadogan, HQ AFLC/DEM, the component lists and their relative weights were necessary for the formulation of a component model rating system for each F/I asset (4).

As a result of the FIPAT studies, HQ AFLC began work on a program called Facility Infrastructure Management Aid (FIMA). This computer-based facility management system was designed to "objectively determine the condition of base facility infrastructure assets, predict their time to failure, and recommend priorities for repair and replacement" (40:9). Data collected during the FIPAT studies formed the basis of the component models used in FIMA.

Condition Factors (CFs), numerical values assigned to each component based on current information, were used as an indicator of component condition. The overall system condition was objectively determined by combining condition factors for various components into an overall Condition Inventory (CI). FIMA uses the CI, along with additional database information and user interaction, to "identify problems, guide the user through an economic analysis of potential solutions, and prioritize the recommended actions" (20:1).

In March 1989, Coyne Kalajian Inc. (CKI) developed a demonstration program, using expert system technology, based on the FIMA component model for back-up power generation systems. According to AFLC/DEM:

> The net result of this effort is a user-friendly expert system which uses the knowledge of AFLC experts. The program interacts with users and multiple databases to identify problems, guide the user through an economic analysis of potential problems, and prioritize recommended actions. (20:1).

Though the CKI expert system received good reviews, little progress has been made to implement the program.

FIMA was tested, and shown to be effective, one other time after the CKI demonstration. During an ExpertR class held at Wright-Patterson Air Force Base, an expert system was written which successfully queried users and analyzed a WIMS database to draw conclusions and make recommendations for maintenance and repair of roofing problems (38).

A primary drawback to implementing the FIMA system is that purchase of an expensive, mini-computer based expert system shell, ExpertR, is required at each base. Additional programming is also needed in the existing Work Information Management System (WIMS) computer system currently used by Air Force Civil Engineering (20:2).

<u>USAFA Infrastructure Management System (IMS) Study</u>: In March 1989, the United States Air Force Academy (USAFA) published an executive report detailing their initial investigation into the feasibility of a campus wide Infrastructure Management System (37). The proposed IMS, a management information system which covers all facility assets, is intended to collect data to assess the condition and maintenance actions required for each asset (37:9). The study was conducted with three basic objectives in mind: 1) the development of sound, defensible

budgets, 2) avoidance of any surprise equipment failures, and 3) optimization of the Academy's operations and maintenance investment (37:3).

In order to meet the second objective, avoidance of any surprise equipment failures, the report recommends an automated Component Modeling Program coupled with a manual Field Survey Program. The Component Modeling Program is intended to "highlight component breakdown frequency and maintenance and repair cost activity that is inconsistent with a component's historical breakdown frequency or maintenance and repair cost" (37:3). The Field Survey Program is designed to manually assess the condition of various components and enter the condition data into the Work Information Management System (WIMS) computers currently used by the Academy. This information could then be accessed and used by the Component Modelling Program (37:3,15,19).

The report recommended that further research be conducted into the actual development of the IMS. HTX International was contacted to develop a proposal to integrate their Component Inspection Decision Support System (CIDSS) with the Air Force's existing WIMS database. Though HTX is looking into the integration, little work has actually been accomplished (7). CIDSS is reviewed below.

U.S. Army. In January 1990, HTX International, Inc., under contract to the U.S. Army, developed the Component Inspection Decision Support System (CIDSS). The computer program provides a method to optimize the maintenance and repair of buildings and building components. It fulfills a specific need for the Directorate of

Engineering and Housing (DEH), the Army's equivalent to the Air Force's Civil Engineering and Services:

> DEH currently has no optimal method to determine and to maintain data on the status and conditions of buildings and then utilize this determination to (1) justify the need for repair or construction work, (2) group the work requirements into projects, and (3) justify budget requests for required/projected work. There is also no viable method for prioritizing the work requirements to ensure that critical funds and manpower are not expended on unnecessary projects. (23:Chap 1,2).

CIDSS is an extensive Data Base Management System (DBMS) which provides a systematic ranking for individual buildings based on the building's condition and its critical mission priority. Condition of each building, and its associated components, is determined through routine inspections (CIDSS even schedules the inspections) coupled with objective and subjective data entered into the computer. The program also provides project management capabilities and "what if" sensitivity analysis of component criteria weights.

CIDSS is currently operational at Fort Riley, Kansas. Data for 32 buildings has been loaded into the system. Data for additional buildings will be accumulated and loaded over the next three to five years depending on the number of inspector positions approved for funding. According to Jim Couple, the CIDSS System Operator at Fort Riley, the system is just beginning to provide cost effective building maintenance management (5).

Many of the DBMS features available with CIDSS are already available to Air Force Civil Engineering through the Work Information Management System (WIMS), though effectiveness of this system has been impeded by lack of adequate training and poor user understanding of system capabilities (2:7). FIMA, described above, would add building

and critical component ranking capabilities, similar to those found in CIDSS, to the WIMS computer. Increased levels of training and enhanced user awareness would make the WIMS/FIMA combination a welcome addition to the infrastructure assessment capabilities throughout civil engineering. As an alternative to the FIMA/WIMS combination, CIDSS can also be ported to the WIMS with very little modification (see USAFA IMS reviewed above), allowing use of existing database information combined with full CIDSS capabilities (7).

Though CIDSS applies only to buildings and their associated component systems, the concepts it uses can be applied to any facility infrastructure system with little or no modification. Furthermore, since CIDSS uses the ORACLE Database with Structured Query Language (SQL) capabilities, it can be easily combined with many existing expert systems to provide an intelligent user interface (7).

U.S. Army Construction Engineering Research Laboratory (USACERL). USACERL is a government agency specializing in research of all facets of construction engineering. They are currently working on the development of condition indices for several facility infrastructure systems. One completed example of their work is a program called PAVER. This program is used to track information on paved roadway surfaces. PAVER estimates the pavement condition based on various data which includes physical inspection, construction type, and use.

USACERL, however, has done very little research in the area of electrical distribution system condition assessment. According to Mr. William Taylor, Electrical Engineer for USACERL, development of condition indices for electrical distribution system components is in

its infancy; it will be many months before any substantial information on this subject is available for review (41).

National Institute of Standards and Technology - Center for Building Technology (NIST-CBT). Considered to be the nation's leading building research laboratory, NIST-CBT "focuses on developing technologies for predicting, measuring , and testing the performance of building materials, components, systems, and practices" (32). No information on electrical distribution systems was available because NIST-CBT focuses primarily on components and subsystems within the actual building structure rather than public works infrastructure systems designed to support large complexes.

Hansen Software, Inc. Hansen Software, Inc. specializes in the design and development of computer software and services related to public works infrastructure. The main thrust of their software is to "help manage the repair, rehabilitation, and replacement " of facility infrastructure assets (12). A review of specifications for the Electric Transmission, Distribution, and Substation Management System (ETDSMS), currently under development by Hansen Software, was conducted as part of this research.

The ETDSMS is an extensive Data Base Management System (DBMS) designed to track all facets of an electric distribution system. It operates on an "installation-to-replacement" concept, where every single component in the system is covered. The ETDSMS is designed to consolidate operations, maintenance, construction, engineering, and customer information into a single DBMS. System logic is incorporated into the design of the DBMS to provide a cross reference of each

component, from the largest transformer to the smallest protective device (12:2). The integrated network formed by this system provides an ideal pool of information which could be easily accessed to aid in overall system condition assessment.

An earlier, less comprehensive version of this program, called the Electric Distribution Management System (EDMS), is currently in use at numerous public utilities and municipalities across the United States and Canada. According to Chris Saill, Senior Consultant for Hansen, the company began implementation of the updated version in July 1991 (36).

Hansen Software's Structured Query Language (SQL) Oracle Database is especially well suited for interface to rules-based expert system technology. An expert system could be designed to access historical DBMS records which are often the best source of predictive repair, rehabilitation, and replacements of components within the electrical distribution system (17:16).

Supervisory Control and Data Acquisition (SCADA). Though not actually a rating scheme, SCADA can be used to provide an extensive amount of data to aid in condition assessment of electrical distribution systems. SCADA provides instantaneous readout data and real time monitoring of any component in the electrical distribution system. This information can be used for balancing load distribution, isolating fault locations, or a myriad other possibilities (14). The data storage capabilities are of particular interest to this research. As real time data is collected, it is stored in a retrieval system. This data can later be accessed and used in other applications, such as an expert

system. Historical trend analysis can be accomplished, at the component level, to aid in short and long term planning (29).

Currently, the only base in the Air Force with a fully operational SCADA system is Robins Air Force Base. The system turned out to be a sound investment, saving almost $450,000 in its first full year of operation. The installation cost was approximately $475,000, resulting in a project payback of just over one year. The primary savings were the result of demand metering coupled with load shifting using excess generator power during peak operating times (14). The Robins SCADA system would require some minor modifications to allow external interfacing with its database system (29).

Critical Component Modelling

Critical component models are often determined through a condition inventory. The system under study is broken down into its basic components, and those components further broken down into subcomponents. To adequately describe the condition of the system, enough critical components and subcomponents must be used (18:atch 1).

As an example of this process, an automobile could have five critical components which describe its condition; chassis, powertrain, body, support, and human factors. Each of these components could further be described by a set of subsystems. The chassis, for example, could be broken into two subsystems, the frame and the suspension. The suspension might consist of coil springs, tie-rods, and shock absorbers. Following this process, a model completely describing the automobile, in terms of its component parts, could be developed. A set of factors, or measurement criteria used to describe the condition of those parts could

then be developed. For instance, wheel alignment, exhaust emissions, cylinder compression, and body rust are factors which affect various components in the automobile.

The process described above can easily be applied to an electrical distribution system. The complexity of the system, however, would require many components, subsystems, and factors be identified, dictating the development of a sophisticated weighting algorithm. Due to the sophistication involved, a group of experts should be involved in determining the makeup of the model and in choosing the evaluation criteria (40:21). The Delphi technique used to achieve this "group" consensus is detailed in Chapter III.

Expert System Applications

Artificial intelligence (AI) is one of the fastest growing areas in computer applications. Perhaps the most significant success story within the AI field is the development of "expert" or "knowledge-based" systems. According to the Electric Power Research Institute, expert systems are "designed to represent and apply the factual knowledge of experts to solving problems in their domain of expertise" (11:Sec 1,1). Another definition describes an expert system as a program "capable of carrying out a task generally regarded as being difficult and requiring some degree of human expertise" (25:9).

Expert systems have been successfully applied to a wide range of tasks dealing with construction engineering and maintenance. According to Charles Culp, "Expert systems offer several advantages that help assure that the right maintenance is done at the right time" (6:24). One of the key advantages is having a substantial amount of expertise at

the maintenance site; an expert system does not require sleep or breaks. A second advanta'je is that information presented is context dependent; its presented as needed and based on previously entered or inferred data. A final advantage is that detailed records can be kept; past data is saved for later use (6:24-26). Dennis Reinhardt states, "Artificial intelligence (AI) systems are emerging as an effective tool for troubleshooting and maintenance problems" (33:18). Recent applications of expert systems in Air Force Civil Engineering include a system which aids in the engineering design of electrical distribution systems by analyzing connectivity problems associated with providing a direct path for electricity to flow from source to load (28:3-5). Another application involves an expert system to properly process work requests in civil engineering (8:23).

Electric Power Research Institute (EPRI). EPRI is a private organization, under sponsorship of the nation's electric utility industry, which conducts research "to advance capabilities in electric power generation, delivery, and use in the public interest, with special regard for efficiency, reliability, safety, economy, and environmental concerns" (10:intro). EPRI's report, Development of Expert Systems as On-Line Power System Operational Aids, details the development of a prototype Customer Restoration And Fault Testing (CRAFT) program.

EPRI's engineers developed the CRAFT prototype expert system as a method to demonstrate the feasibility of using expert system operational aids in the electric utility control center environment. The specific topic of fault isolation and power restoration was selected because there is a large, experienced source of knowledge in the numerous

dispatchers assigned to an electric utility (9:sec 1,3). The research was co-sponsored by Puget Sound Power and Light (PSPL) in Bellevue, Washington.

CRAFT helps the dispatchers perform on-line, real time analysis of the power transmission system once a fault has occurred. When automatic operations of switching circuits fail to restore power to all customers, the dispatcher may be able to perform additional, manual switching operations to restore power. However, the dispatcher must first analyze the switch settings after all automatic operations are complete. By knowing the intended operations of these switches, the dispatcher may be able to determine the location of the fault and, if successful, operate the correct switches to restore power (9:Sec 1).

The knowledge-base developed for this application consisted of approximately 200 production rules developed after extensive interviews with all PSPL dispatchers (9:Sec 2,4). During the interviews, the dispatchers identified the reasoning and several heuristics which they typically used in solving fault isolation problems. The available empirical data, dispatcher procedures, and heuristics were then encoded into the knowledge base using OPS83 production system language. The expert system provided for logical flow by grouping rules under tasks where rules under each task are selected until the task is completed or until no more rules are applicable (9:Sec 2,9).

The prototype expert system was extensively tested by simulation of on-line activity at PSPL. The report concluded that "expert system tools can be valuable aids for human operators in utility control centers" (9:Summary,3). This conclusion was echoed by the PSPL

dispatchers who are anxious for the system to be completed and installed on-line. EPRI, PSPL, and the National Science Foundation are cosponsoring a continuance of this project to implement CRAFT on-line at PSPL (9).

Summary

This chapter reviewed available research related to designing an expert system for quantifying the condition assessment of an electrical distribution system. Several attempts have been made, both in government and in private sector, to provide an adequate condition assessment model for facility infrastructure assets. Though a few studies showed promise, only one, Hansen Software's ETDSMS, was successfully completed for the electrical distribution system. A component modelling technique was also reviewed and its applicability for use in this research was demonstrated. The final area of this chapter discussed current trends in artificial intelligence and the usefulness of expert systems to the area of engineering operations and maintenance.

III. Methodology

Overview

The process of building an expert system is iterative, involving knowledge acquisition followed by system design and, finally, implementation. This chapter will outline the specific steps required to design a typical expert system. Since the most crucial step in expert system design is knowledge acquisition, a separate section in this chapter is devoted to the primary method used to gather that knowledge, the Delphi Technique.

Expert System Development

An expert system can be developed using a five step process which begins with problem identification and familiarization. The second step is preliminary knowledge acquisition, which is followed by development of the prototype expert system. The last two steps include primary knowledge acquisition and, finally, system implementation and refinement (16).

Problem Identification. The first step in designing the expert system is problem identification and familiarization (16:42-43). The researcher must clearly state the objective as well as the primary goals needed to attain that objective (11:Sec 2,4). Chapter I outlined the specific problem area along with the research objective. The investigative questions discussed in Chapter I describe the primary goals of this research.

The researcher must possess a basic knowledge of the subject in crder to understand the information garnered from the domain expert during the knowledge acquisition process. Therefore, the researcher must completely familiarize himself with the domain, or area under study (31:163). Familiarization of the domain was accomplished through an exhaustive review of applicable literature as described in Chapter II.

Preliminary Knowledge Acquisition. After problem identification and familiarization, the researcher is ready to begin the knowledge acquisition process. Knowledge is considered to be more than just data. According to the Electric Power Research Institute,"[knowledge] consists of facts, relations, 'rules of thumb' and other important constructs that enable seemingly intelligent observations and conclusions to be evoked" (11:Sec 1,6). Domain experts, individuals with expertise in the area under investigation, possess the knowledge required to make the expert system operate. The researcher must somehow transfer the knowledge from the domain expert into the expert system. This can be accomplished by interviews or surveys with identified domain experts, followed by programming the information into an expert system shell.

Preliminary knowledge acquisition is used to develop a prototype expert system as described in the following section. Ken Pederson, in his book Expert Systems Programming: Practical Techniques for Rule-Based Systems, recommends an unstructured interview process to allow the domain expert freedom to express his or her ideas fully (31:163-169). The interview consists of general discussions relating to the investigative questions outlined in Chapter I. The results of the

interview can be used to further refine the investigative questions if necessary.

Preliminary knowledge acquisition for this thesis followed the pattern described above. An open-ended interview with a single domain expert (30) yielded the necessary information to begin development of a prototype expert system, as discussed in the next section.

Develop Prototype. Once preliminary knowledge acquisition is complete, a prototype expert system can be developed. The primary purpose of the prototype is to validate the applicability of using an expert system to solve the identified problem. It is also used to aid the researcher in gaining additional information concerning key areas of the problem.

The prototype should be advanced enough to provide reasonable, though not necessarily correct, answers across most of the domain problems (11:Sec 2,11-12). Depth, breadth, and correctness of answers are provided through additional knowledge acquisition and program refinements during later stages of development.

The prototype expert system for this research was developed after an initial interview with the domain expert. The main thrust of the interview was to develop a component model of a "typical" electrical distribution system. The process resulted in a model with three primary critical component systems and two primary system factors. Each component system and primary system factor was further broken down into sub-systems and sub-factors.

A majority of the interview was spent on discussions of the relative weights of each component system or factor compared with the

others. The key indicators and weights of the sub-systems and sub-factors were also discussed. The prototype component model is shown in Table 1. The prototype expert system developed from this model demonstrated the feasibility of using expert system technology for this specific problem.

TABLE 1

PROTOTYPE COMPONENT MODEL OF A TYPICAL
ELECTRICAL DISTRIBUTION SYSTEM

CRIT COMPONENT SYSTEMS	SUB-SYS/FACTORS	COMPONENT WEIGHT	OVERALL WEIGHT
Power Transformation			250
	Type/integrity of insulation	50	
	Condition of connections	50	
	Insulator condition	50	
	Loading	50	
	Protective Devices	50	
Power Distribution			250
	Corrosion at connections	75	
	Supporting Structure	75	
	Conductor Loading	50	
	Insulation Condition	50	
Substation Condition			250
	Rslts of Therm. Surv.	75	
	Avg Age of Devices	60	
	Corrosion at Connections	60	
	Relays Checked/Adj Reg	55	
PRIMARY FACTORS	SUB-FACTORS		
System Integration			100
	System Engineer	35	
	Coordination Study	20	
	Component Integration	20	
	System Capacity	25	
System Maintenance			150
	Maintenance Plan	50	
	Thermographic Survey	50	
	Power Outages	50	

Primary Knowledge Acquisition. The steps leading to primary knowledge acquisition serve two purposes. The first is to allow the researcher to gain familiarity and understanding of the problem. The second is to show that an expert system solution to the problem is possible. The final two steps of expert system development, primary knowledge acquisition and system implementation/refinement, are designed to eliminate any "holes" which exist in the knowledge base and to further refine the expert system (11:Sec 2,12).

During primary knowledge acquisition, the researcher focuses on adding information to the knowledge base developed earlier (11:Sec 2,12). Since it is difficult to acquire all knowledge at one time, the addition of knowledge is best accomplished using an iterative process where the domain experts are contacted several times during the course of the project. Gathering knowledge a little at a time will aid in developing a more refined expert system (31:169). The Delphi Technique, described later in this chapter, uses an iterative process to achieve group consensus and was employed as the primary tool for knowledge acquisition.

System Implementation/Refinement. Once the primary knowledge acquisition is complete, the knowledge is translated into the rule-based format required for expert system implementation (21:9-10). As with any computer program, the actual implementation is the start of the refinement process. The last two steps are continuously repeated. As more knowledge is gained, further refinements are made to the system (11:Sec 2,13). Chapter 5 of this thesis details the development of the rule-base used for this expert system.

Delphi Technique

This section discusses the research methodology used for the primary knowledge acquisition step while developing the expert system. Many experts in the area of Artificial Intelligence (AI) recommend using a single domain expert for knowledge acquisition in order to keep the problem simple and to avoid conflicts between multiple experts (22). However, when the problem solution must cover a broad range, as in the case of assessing a "typical" electrical distribution system, a larger number of experts should be consulted to provide the necessary generalization. Therefore, the Delphi technique was employed to gather information from a panel of 15 experts on electrical power distribution.

Background. The Delphi technique was developed by the Rand Corporation in the early 1950's as a long range forecasting tool (26:18). It has been described as "a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem" (27:3). In its most widely used form, the Delphi technique is an iterative opinion survey conducted on a panel of domain experts. The technique achieves a consensus of opinions through a combination of multiple iterations and anonymous feedback (42:38). The anonymity of responses leads to one of the Delphi techniques greatest advantages, that of reducing the effect of a "dominant person" imposing his or her opinions, regardless of the correctness of those opinions, on other panel members (34:55-56). Another advantage is in the controlled nature of the feedback. This control "acts as a way to reduce noise from the responses" by allowing the one or two 'odd' experts a chance to review

and possibly change their opinions with respect to the entire group (40:24-25).

Selection of Experts. begin the Delphi process, one must first select the expert participants. For the purposes of this research, the term "expert" is defined as individuals who possess special skills or knowledge derived from a mix of education, training, and experience (35:26). Experts are further classified as electrical engineers with ten or more years experience designing power distribution systems, or as senior maintenance supervisors with ten or more years maintaining electrical distribution systems. An equal mix between engineers and technicians is desired to lend objectivity and rigor to the Delphi process, a process often criticized as lacking rigor (35:17).

The recommended number of Delphi participants ranges from ten to fifty (40:27). Due to the small number of experts available in the Air Force, this research used only fifteen participants. Experts were solicited from several major commands to provide a cross sectional view of electrical distribution systems throughout the Air Force as well as to ensure the minimal number of qualified participants.

Once names from participating commands were received, each recommended expert was contacted via telephone to confirm his or her level of expertise. In addition, the Delphi process was explained and estimated time commitments were discussed. Only those experts who met the experience criteria and who were willing to volunteer the necessary time for completion of the Delphi questionnaires were included. One individual was eliminated during this process because he had recently retired from the military and did not wish to volunteer.

Nine of the fifteen selected experts were electrical engineers, four were electrical superintendents, and the remaining two were exterior electric shop foremen. The personnel were assigned to Air Force Logistics Command (AFLC), Strategic Air Command (SAC), Tactical Air Command (TAC), United States Air Forces Europe (USAFE), and the Air Force Engineering and Services Center (AFESC).

Development of First Round Questionnaire. The next step in the Delphi process is the development of the initial survey instrument. The available literature does not describe any set format or outline for the questionnaire. The knowledge acquisition phases described above recommended use of an unstructured knowledge gathering technique. Therefore, this questionnaire was designed around an open-ended question format roughly paralleling the first five investigative questions outlined in Chapter I. The complete first round Delphi package is included as Appendix A.

The experts were asked to provide free-form written responses to each of the questions. This open-ended format allowed all experts to freely express their opinions on critical electrical distribution system components, factors affecting the distribution system, and relative weights of the selected components and factors. Experts were allowed to identify as many subsystems, critical components, and system factors as they thought necessary to compl. .ely describe the condition of the electrical distribution system.

Ten participants responded within two months of the questionnaire mailing. The five experts not responding cited heavier than expected job requirements as the primary reason for not responding. Two also

stated that the questionnaire was difficult to understand and therefore would have required more time than originally anticipated. All fifteen experts indicated they would participate in the second round if time permitted.

Analysis of First Round Responses. The first round responses were analyzed by grouping the key subsystems and key system factors identified by each expert. The total number of experts selecting each key subsystem or key system factor was determined along with the average weighting factor assigned to each category. Six key subsystems were identified: substation, distribution transformer network, primary distribution cable network, secondary distribution cable network, primary switchgear, and protective devices. Four key system factors were identified: maintenance and inspection, diagnostic tools, outage records, and type of system. Appendix D, Tables 3 and 10, contain summaries for the key subsystems and the key system factors. A similar analysis was conducted for the critical components identified under each key subsystem and for the critical subfactors identified under each key system factor. Summaries of these results are contained in Appendix D, Tables 4-9 and 11-14.

Written responses for the evaluation criteria of critical components and subfactors along with the condition criteria are summarized in Appendix C. Four of the respondents did not complete the criteria section for many of the identified components. The condition criteria was used to establish the limits and range of the stated evaluation criteria. The condition criteria formed a basis for many of the quantifiable portions of the model developed in Chapter IV.

<u>Development of Second Round Questionnaire</u>. The purpose of a second round questionnaire in the Delphi process is to give each expert a chance to review the inputs of all other experts and to try to achieve a consensus on opinion from all of the experts involved. Therefore, a summary of the first round responses was incorporated into the second round questionnaire. The complete second round Delphi package is included as Appendix B.

Because the first round required an excessive amount of time to complete, emphasis was placed on formatting the second round for quicker response time. Round one summaries identified all of the selected subsystems, components, and factors. It also showed the number of experts who selected each item and, finally, listed the average weighting factor for each item. Participants were asked to review the summaries and then to weight the key subsystems, critical components, key system factors, and critical subfactors. Experts were asked to use a relative rating scale of 1 - 10, with 10 being the highest.

Some of the critical component lists contained as many as nine entries. In order to keep the number of critical components in each subsystem to a manageable size, the participants were asked to weigh only 70% of the components listed for most of the subsystems. This helped ensure the experts would pick only those components they felt were truly critical. A similar strategy was applied to keep the number of key system subfactors within usable bounds.

Second round packages were sent to all fifteen of the original experts. Nine of the packages were returned within one month.

Analysis of Second Round Responses. Central tendency characteristics of the responses can be used to statistically measure the level of agreement between the various responses to the questionnaire. The required rank ordering of responses implies the ordinal scale of measurement be used. The resulting measurement of central tendency is either the median or the mode. This research was interested in actual frequencies of experts either including or not including various responses, therefore the mode is considered the more appropriate of the two measures (13:87-91). Consensus on a given response was determined when at least 70% of the responses fell within the mode. Responses not acquiring the 70% consensus rate were discarded.

Initial analysis of round two responses eliminated two key subsystem (secondary distribution cable network and protective devices) and one key system factor (system type) from the model. In addition, the critical component lists and critical subfactor lists were reduced to between three and five items each. Appendix D, Tables 15-23, contains summaries of round two responses.

The next step in the analysis process was to calculate the normalized weights given each response. This was necessary to compensate for possible differences in numerical scales used by the various experts (40:30). For example, the normalized weight factors for key subsystems were calculated by taking each expert's weight for a particular subsystem and dividing by the sum of the weights assigned to all selected subsystems. Appendix D, Tables 15-23, summarizes the normalized weight factors for all selected round two responses. The key

subsystems, critical components, and critical factors for which consensus was established, along with their average normalized weights, were used in the final quantitative model and subsequent expert system.

Summary

This chapter provided an overview of the methodology used in developing an expert system. Five steps in the development process were described along with a brief outline relating the research objective to each step in the process. This chapter also discussed the methodology used to acquire expert opinions on critical components and factors within an electrical distribution system. The lists of key subsystems, critical components, key system factors, and critical subfactors for inclusion in the final expert system was determined based on the consensus of the expert panel through employment of the Delphi technique.

IV. Derivation of Component Model

Overview

This chapter focuses on the derivation of a component model for a typical electrical distribution system. The component model is broken down into a set of key subsystems and key system factors. Each subsystem is further broken down into separate critical components which are used to assess its condition. Likewise, each key system factor is broken into its critical subfactors. The condition of each critical component and critical subfactor is described in terms of a numerical value, the condition index.

Condition indices are calculated from data provided by component test results, existing records, or visual inspections. Many of the condition indices represent simple linear equations due to the large number of components involved in a particular critical component group. A few condition indices, however, were better suited to representation by discrete values assigned after matching observed characteristics of the item with a criteria list containing numerical scores, thus allowing easier encoding of the model into an expert system.

Once condition indices have been calculated for each critical component within a key subsystem, they are combined into a condition index for that particular key subsystem. The individual key subsystem condition indices are then combined to form another condition index representing all key subsystems. Similarly, the critical subfactor condition indices are combined until an overall key system factor condition index results. In the final step of the process, the key

subsystems condition index is combined with the key system factors condition index to arrive at a single condition index representing the entire electrical distribution system.

The results of the Delphi survey were used to select each of the various components and subfactors used in the model. The evaluation and condition criteria detailed by the experts who responded to the first round Delphi survey were further used to aid in establishing the actual numerical condition indices of critical components and subfactors. Additional information from interviews with various experts, review of literature, and the researcher's experience with electrical distribution systems completed the data necessary to formulate an accurate, quantifiable condition index.

General Description of Electrical Distribution System Component Model

As stated above, the Delphi surveys were the actual instruments used to develop the component model which follows. The model contains only those key subsystems and key system factors, along with their corresponding critical components and critical subfactors, which 70% or more of the responding experts agreed should be included. Information on items achieving consensus is contained in Appendix D, Tables 15-23.

The resulting model, shown in Table 2, contains four key subsystems which can be used as indicators of the physical condition of the overall distribution system: substation, distribution cable network, switchgear, and distribution transformer network. The model also contains three key system factors which can be used as indicators of overall system maintenance management: maintenance and inspection, diagnostic tools, and outage records.

TABLE 2

ELECTRICAL DISTRIBUTION SYSTEM
COMPONENT MODEL

KEY SUBSYSTEMS	CRITICAL COMPONENTS	COMPONENT WEIGHT	SYSTEM WEIGHT	OVERALL WEIGHT
				0.67
SUBSTATION			0.33	
	Breakers	0.30		
	Primary Transformer	0.27		
	Relays	0.27		
	Bypass Switches	0.16		
DISTRIBUTION CABLE NETWORK			0.28	
	Conductors	0.29		
	Supporting Structure	0.28		
	Other Components	0.23		
	Terminations	0.20		
SWITCHGEAR			0.23	
	Switch	0.40		
	Relays	0.32		
	Case	0.28		
DISTRIBUTION TRANSFORMER NETWORK			0.16	
	Protective Devices	0.30		
	Insulation Medium	0.26		
	Characteristics	0.24		
	Case	0.20		
KEY SYSTEM FACTORS	CRITICAL SUBFACTORS			0.33
MAINTENANCE/INSPECTION			0.41	
	Manning/Experience	0.28		
	Training Level	0.27		
	Maintenance Plan	0.25		
	Proper Equipment	0.20		
DIAGNOSTIC TOOLS			0.32	
	Coordination Study	0.29		
	Drawings/Maps	0.29		
	Thermographic Survey	0.22		
	Manufacturer's Instr.	0.20		
OUTAGE RECORDS			0.27	
	Cause	0.39		
	Frequency	0.36		
	Duration	0.25		

The key system factors were included so the overall system condition index would be reduced to reflect poor maintenance management. A majority of the experts agreed that inadequate or improper maintenance of the electrical distribution system will result in a degradation of that systems overall condition. The relative weighting of the key subsystems versus the key system factors was adjusted to allow heavier weighting of the actual physical condition.

Component/Subfactor Condition Indices. The key subsystems and key system factors were further broken down into critical components and critical system subfactors. For each of the critical components and critical subfactors listed in Table 2, a separate numerical condition index was calculated.

Each condition index resulted in a number between 0 and 100, with 0 representing a totally failed component or valueless subfactor. A score of 100, on the other hand, represents the maximum allowable rating for a particular component or subfactor. Many of the components and subfactors were evaluated based on several different parameters. The sum of the scores from all applicable parameters for a particular component or subfactor was used to determine the condition index. For example, if a component is evaluated based on four different parameters, each parameter score would range from 0 to 25, and the sum of the four scores would remain between 0 and 100.

The primary source of information used to determine the condition indices was the expert responses to the first round Delphi survey listing evaluation and condition criteria. This listing is included as Appendix C. Where expert responses were inadequate to derive the

condition indices, additional information was obtained from interviews, personal experience of the researcher, and readings from technical literature on electrical distribution systems.

According to AFLC/DEM, the overall numerical rating system should be broken down into three condition categories based on score: good, fair, and poor (19). The numerical range corresponding to these categories are: 80 - 100 for good, 60 -79 for fair, and 0 - 59 for poor (40:40). The Delphi survey was structured to obtain evaluation and condition criteria based on these categories. The condition criteria given by various experts was used to determine ranges within each category as well as to determine end and midpoints, on a 0 - 100 scale, for evaluation purposes.

Key Subsystem/Key System Factor Condition Indices. The condition index for each key subsystem and key system factor was calculated using the weighted sum of the components or subfactors comprising that subsystem or system factor. The weights were determined by calculating the average relative normalized weight given each component by the experts responding to the second round Delphi survey. These weights appear in Table 2 under the column labeled Component Weights and are summarized in Appendix D, Tables 16-19 and 21-23. An example for the switchgear condition index, CI(Switchgear), follows:

$$CI(Switchgear) = 0.40*CI(SS) + 0.28*CI(SC) + 0.32*CI(SSR) \quad (1)$$

where

CI(SS) = Switch condition index

CI(SC) = Case condition index

CI(SSR) = Relays condition index

Total Subsystem/System Factor Condition Indices. After calculating individual key subsystem and key system factor condition indices, the next step was to determine single condition indices for the subsystems and for system factors. Once again, the average relative normalized weights from the second round Delphi survey were used. The subsystems condition index was calculated using the weighted sum of the individual key subsystems listed in Table 2. Likewise, the system factors condition index used the weighted sums of the key system factors. The weights used for calculation appear in Table 2 under the column labeled System Weights and are summarized in Appendix D, Tables 15 and 20. An example for the condition index for system factors, CI(Factors), follows:

$$CI(Factors) = 0.41*CI(Maint) + 0.32*CI(Tools) + 0.27*CI(Outage) \quad (2)$$

where

CI(Maint) = Maintenance/Inspection condition index

CI(Tools) = Diagnostic Tools condition index

CI(Outage) = Outage Records condition index

Overall Electrical Distribution System Condition Index. The overall condition index for the electrical distribution system was calculated using a weighted sum of the subsystems condition index and the system factors condition index. The weights were determined by a combination of personal interviews (7; 14; 15; 29; 30) coupled with researcher's experience and judgement. As discussed earlier, the key subsystems are weighted heavier to allow the actual physical condition of components to contribute more to the condition index. These weights

appear in Table 2 under the column Overall Weights. The overall electrical distribution system condition index, CI(EDS), was calculated as follows:

CI(EDS) = 0.67*CI(Subsystems) + 0.33*CI(Factors) (3)

where

CI(Subsystems) = Subsystems condition index

CI(Factors) = System Factors condition index

<u>Derivation of Electrical Distribution Condition Indices</u>

The condition indices derivation methodology described above was applied to all selected critical components and critical subfactors. The following section is broken down first by key subsystem or key system factor, and then by individual critical components or subfactors.

<u>Substation</u>. The condition of the substation can be accurately defined by the condition of several of its critical components. These critical components are: substation breakers, bypass switches, relays, and primary transformer (if present). The condition index for each critical component is calculated below, followed by the condition index for the substation, CI(Substation).

<u>Substation Breakers</u>. The substation breakers were evaluated based on three parameters: visual inspection, tests for oil dielectric strength and proper operation, and age. Since a typical substation contains several breakers, the number of breakers evaluated in each category was used to develop a linear equation for the condition of each parameter. The number of breakers was adjusted by a scaling factor (in this case 2 for fair breakers, and 4 for poor breakers) to adjust for

differences in severity of the evaluations. This allows the penalty for breakers rated poor to be twice as severe as the penalty for fair breakers.

Experts 1, 6, and 7 agreed that a visual inspection is required to determine the condition of the substation breakers. Visual inspections should check for corrosion, arcing or burning of contacts, and tracking of insulators. According to Expert 2, a breaker is in fair condition if there are minor corrosion stains on paint, minor contact burning, or insulator contamination. He would rate a breaker poor if there were extensive corrosion resulting in cabinet damage, contact pitting, or visible insulator tracking. Using these comments on amount of corrosion, contact wear, and tracking, and factoring in the number of circuit breakers involved yielded the following equation:

$$SB1 = 34 - [2*(\#\text{ fair breakers}) + 4*(\#\text{ poor breakers})] \tag{4}$$

where

fair breakers = number of breakers in substation fitting description for fair

poor breakers = number of breakers in substation fitting poor description

In addition, periodic test results for oil dielectric strength (if breakers use oil as an insulating medium instead of vacuum), and proper operation of breaker under fault conditions should be used. Combining the comments from Experts 1, 3, and 7 yielded the following equation:

$$SB2 = 33 - [2*(\#\text{ fair dielectric}) + 4*(\#\text{ poor dielectric}) + 4*(\#\text{ no operation})] \tag{5}$$

where

fair dielectric = number of oil circuit breakers with dielectric test results between 22-27 KV

poor dielectric = number of oil circuit breakers with dielectric test results lower than 22 KV

no operation = Number of circuit breakers which did not operate properly under load (includes both oil circuit breakers and vacuum circuit breakers)

The final parameter, identified by Expert 6, involves the age of the circuit breaker mechanisms. Circuit breakers less than five years old are considered in good condition, those between 10 and 25 years of age are considered fair, and those over twenty five years of age are in poor condition. This yielded the following equation:

$$SB3 = 33 - [2*(\# \text{ CB middle age}) + 4*(\# \text{ CB old age})] \quad (6)$$

where

CB middle age = number of substation circuit breakers between 10 and 25 years old

CB old age = number of substation circuit breakers greater than 25 years old

The condition index for substation circuit breakers, CI(SCB), is than calculated by the following equation:

$$CI(SCB) = SB1 + SB2 + SB3 \quad (7)$$

Where

SB1, SB2, and SB3 = separate substation breaker parameters defined in equations (4), (5), and (6) above

<u>Bypass Switches</u>. All responding experts agreed that visual inspections of the bypass switches were required for condition assessment. Specific areas to check included ease of operation, contact

wipe, and amount of corrosion and pitting on the contacts. A single linear equation, based on number of bypass switches evaluated in each category, was derived. Again, scaling factors were used to adjust the severity of each rating such that the condition index was reduced appropriately.

According to experts 2, 5, and 8, a good bypass switch should be easy to operate, have no pitting or burning on the contacts, and be corrosion free. A bypass switch would be rated fair if it has stiff operation with adequate contact alignment for proper closure, and minor pitting and burning of the contacts. On the other hand, a poor bypass switch would exhibit extreme effort to close; pitting of the contacts would be easily seen and the arc shorts would be severely burned. These comments yielded the following equation describing the condition index for substation bypass switches, CI(SBS):

$$CI(SBS) = 100 - [6*(\#\ \text{fair switches}) + 12*(\#\ \text{poor switches})] \qquad (8)$$

where

fair switches = number of substation bypass switches exhibiting stiff but proper operation, and showing minor pitting and burning on the contacts

poor switches = number of substation bypass switches which do not operate properly or require extreme effort to close and/or show easily visible signs of pitting and burning of the contacts

<u>Primary Transformers (if present)</u>. The primary transformers are used to reduce the extremely high voltages used for electric power transmission (typically 115 KV and higher) to lower voltages used in a local distribution network (typically 13-20 KV). In many instances, the

local utility which provides the electrical power to a base owns and maintains the primary transformers. If this is the case, then the condition index for substation primary transformers is given full value, as shown by the following equation:

$$CI(SPT) = 100 \quad \text{(if no transformers are present)} \tag{9}$$

However, where the base owns and maintains the primary transformers, the condition of those transformers affect the overall condition of the substation. Experts 1, 4, and 6 identified four parameters to use when evaluating substation primary transformers: visual inspection of case and bushings, age of transformer, loading of transformer, and insulation tests. Therefore, each parameter is given a maximum value of 25 points.

Experts 1 and 4 identified visual inspections as one of the evaluation parameters. A good rating would result if a visual inspection of the bushings showed they were not cracked or leaking, and inspection of the case showed no signs of corrosion. A poor rating, on the other hand, results from bushings which are visibly cracked or leaking, and a case which is severely corroded. This description resulted in the following set of equations:

$$SPT1 = 25 \quad \text{If no cracking, leaking, or corrosion evident} \tag{10}$$

$$SPT1 = 12.5 \quad \text{If cracked, leaking, or corroded} \tag{11}$$

Age was also considered as a parameter to determine the condition of substation primary transformers. According to Expert 1, a transformer is in fair condition if it is between 5 and 20 years old.

Transformers older than 25 years should be rated poor. The following linear equation resulted:

$$SPT2 = 25 - [0.4*(Age)] \tag{12}$$

where

Age = Average age of substation primary transformers, in years

The next evaluation parameter, transformer loading, was also identified by Expert 1. The criteria states that transformers loaded between 100% and 115% of capacity should be rated fair. Transformers loaded greater than 115% should be rated poor. The resulting set of discrete equations follows:

SPT3 = 25	Transformer loaded 85-95% of capacity	(13)
SPT3 = 20	Transformer loaded 95-100% of capacity	(14)
SPT3 = 15	Transformer loaded < 80% of capacity OR loaded 100-115% of capacity	(15)
SPT3 = 10	Transformer loaded > 115% of capacity	(16)

The final evaluation parameter involves test results for the insulation medium. Experts 1, 4, and 6 all identified the oil dielectric strength for transformers using oil for insulation. Test results above 27 KV are considered good, while results ranging between 22 KV and 27 KV are rated fair. If oil dielectric strength drops below 22 KV, then the test is rated poor. A similar analysis for gas insulated transformers yields the following discrete equations:

SPT4 = 25	Oil dielectric > 27 KV OR Good air seal and gas analysis performed every six months	(17)
SPT4 = 17.5	Oil dielectric between 22 KV and 27 KV OR gas analysis performed yearly	(18)

SPT4 = 12.5 oil dielectric < 22 KV
OR no air seal (19)

With all of the parameters defined, the condition index for substation primary transformers, CI(SPT), was calculated as follows:

$$CI(SPT) = 100 \quad \text{(if no transformers are present)} \tag{9}$$

$$CI(SPT) = SPT1 + SPT2 + SPT3 + SPT4 \tag{20}$$

where
SPT1, SPT2, SPT3, SPT4 are the values of the four parameters described by equations (10) through (19) above

Relays. The final critical component in the substation was identified as the substation relays. Though there are numerous relays in the substation, the evaluation criteria suggested by Expert 1 eliminated the need to develop a linear equation using the numbers of components assigned each rating, as accomplished for breakers and bypass switches earlier. The condition criteria depend on how the relays are tested and calibrated by maintenance personnel, and whether or not results of a short circuit analysis/coordination study were used to set the relays. The following discrete equations were used to assign a value to the condition index for substation relays, CI(SR):

CI(SR) = 100 If relays are set according to short circuit analysis and coordination study using primary current inspection (21)

CI(SR) = 75 If relays are set according to short circuit analysis and coordination study using secondary current inspection (22)

CI(SR) = 50 Relays are tested and reset to original settings without the aid of a short circuit analysis and coordination study (23)

The condition index for the substation, CI(Substation), is next calculated by combining the critical component condition indices, described by equations (7), (8), (9), and (20) through (23) above, with the weighting factors found in Appendix D, Table 16. The resulting equation yields:

$$CI(Substation) = 0.30*CI(SCB) + 0.16*CI(SBS) + 0.27*CI(SPT) + 0.27*CI(SR) \quad (24)$$

Distribution Cable Network. The condition of the distribution cable network can be evaluated based on the condition of four of its critical components: conductors, supporting structure, other components, and terminations. The condition index for each of these critical components is calculated below, followed by the condition index for the distribution cable network, CI(Cables).

Conductors. A combination of the comments from Experts 2 and 8 was used to establish the evaluation parameters for conductors. According to Expert 2, condition can be established by a visual inspection of overhead lines for corrosion or damage, and Hi-Pot tests of underground cables. Expert 8 also noted that cable failure history should be taken into account due to the amount of stress fault failures create on a conductor. The condition criteria developed by the experts yielded the following equations:

$$CNC1 = 50 - [1*(\#\ Cables\ 1.5\ HiPot) + 2*(\#\ Cables\ 1.0\ HiPot) + 1*(\#\ OH\ Lines\ Fair) + 2*(\#\ OH\ Lines\ Poor)] \quad (25)$$

where

Cables 1.5 HiPot = number of high-voltage underground cables which tested to 1.5 times cable rating during Hi-Pot test

Cables 1.0 HiPot = number of high-voltage underground cables which tested to 1.0 times cable rating during Hi-Pot test

OH Lines Fair = number of overhead high-voltage lines which show minor signs of corrosion or for which line sag appears to exceed limits

OH Lines Poor = number of overhead high-voltage lines which show extreme corrosion or for which line sag appears excessive

CNC2 = 50 - [2*(# Cables Low FF) + 4*(# Cables High FF)] (26)

where

Cables Low FF = number of overhead and underground high-voltage conductors which have experienced between one and three fault failures

Cables High FF = number of overhead and underground high-voltage conductors which have experienced more than three fault failures

The condition index for distribution cable network conductors, CI(DCNC), was next calculated with the following equation:

CI(DCNC) = CNC1 + CNC2 (27)

where

CNC1 and CNC2 are the conductor parameters calculated in equations (25) and (26) above

Supporting Structure. Supporting structure encompasses the poles and insulators supporting overhead high-voltage lines, as well as conduits and manholes supporting underground high-voltage cable installations. Experts 2, 3, and 4 all agreed that a visual inspection of each system is required to determine its condition. Expert 2's condition criteria was used to develop the following equations:

$$CNSS1 = 50 - [0.5*(\#\ Fair\ Poles) + (\#\ Poor\ Poles)] \tag{28}$$

where

\# Fair Poles = number of poles which have signs of checking or treatment failure and/or number of poles where insulators show surface contamination (no structural damage to insulators)

\# Poor Poles = number of poles which have shell rot (determined by sounding pole) and/or number of poles which have cracked or broken insulators

$$CNSS2 = 50 - [0.5*(\#\ Fair\ Manholes) + (\#\ Poor\ Manholes)] \tag{29}$$

where

\# Fair Manholes = number of manholes or conduit sections which appear muddy but which have a good history of pulling cables

\# Poor Manholes = number of manholes with a history of cable pulling difficulty or number of collapsed conduit sections

Combining the parameters defined by equations (28) and (29) yielded the condition index for the distribution cable network supporting structure, CI(DCNSS):

$$CI(DCNSS) = CNSS1 + CNSS2 \tag{30}$$

Other Components. Several other components were identified as critical in defining the condition of the distribution cable network. The components included items such as switches, sectionalizers, cutouts, reclosures, potheads, and etc. All of these components have been combined into a single category labeled "Other Components." The experts agreed that a visual inspection is adequate to determine the condition of most of these components. Expert 4 also recommended an infra-red scan of the cable network to identify any components developing hot spots; a sure sign of poor component condition. Expert 6 recommended

checking the coordination between fuses and reclosures to ensure both transformers and cables are protected during fault conditions. However, coordination of components is evaluated under the Diagnostic Tools key system factor in a later section and is therefore excluded in this section. The condition criteria from Experts 2, 4, and 7 resulted in the following equations to describe the condition index for distribution cable network other components, CI(DCNOC):

$$CI(DCNOC) = 100 - [(\#\ \text{Fair Components}) + 2*(\#\ \text{Poor Components})] \quad (31)$$

where

# Fair Components	=	number of other components which show minor corrosion but which have no history of faulty operations; infra-red scan should not show hot spots around components
# Poor Components	=	number of components which show excessive corrosion, have a history of faulty operations, or display as hot spots during an infra-red scan

<u>Terminations</u>. The final critical component identified under the distribution cable network subsystem is terminations. Experts 8 and 10 recommend conducting a visual inspection of all terminations to check for corrosion and looseness of connection. Both corroded and loose terminations will show up as hot spots during an infra-red scan (30). Using Expert 10's condition criteria yielded the following equation describing the condition index for distribution cable network terminations, CI(DCNT):

$$CI(DCNT) = 100 - 3*(\#\ \text{Poor Terminations}) \quad (32)$$

where

Poor Terminations = number of high-voltage cable terminations which show signs of visible corrosion, arcing, or looseness (poor condition can be determined if termination shows as a hot spot during infra-red scan)

Combining the critical component condition indices described in equations (27), (30), (31), and (32) with the weighting factors contained in Appendix D, Table 17, yielded the condition index for the distribution cable network, CI(Cable):

$$CI(Cable) = 0.29*CI(DCNC) + 0.28*CI(DCNSS) + 0.23*CI(DCNOC) + 0.20*CI(DCNT) \quad (33)$$

Distribution Transformer Network. The distribution transformer network is comprised of numerous transformers used to transform power from the high voltages used for distribution down to the lower voltages required by the end user. Experts 1 and 2 recommend only transformers rated 100 KVA and higher be evaluated as part of this subsystem. The critical components used to evaluate the distribution transformer network are: insulation medium, condition of case, transformer characteristics, and protective devices. The condition index for each critical component is defined below, followed by the condition index for the distribution transformer network, CI(Transformer).

Insulation Medium. Determining the condition of the insulation medium involves test results for the insulation medium. Experts 1 and 2 identified the oil dielectric strength for transformers using oil for insulation. Test results above 27 KV are considered good, while results ranging between 22 KV and 27 KV are rated fair. If oil

dielectric strength drops below 22 KV, then the test is rated poor. A similar analysis for air (gas) insulated transformers yielded the following discrete equations:

CI(DTIM) = 100	Average oil dielectric > 27 KV OR Good air seal and no visual signs of deterioration	(34)
CI(DTIM) = 70	Average oil dielectric between 22 KV and 27 KV OR minor deterioration of insulation medium is apparent	(35)
CI(DTIM) = 50	Average oil dielectric < 22 KV OR air seal is inoperative and excessive deterioration of insulation is apparent	(36)

Case. Two parameters were identified to describe the physical condition of the transformer case: visual inspection for corrosion, and age). Experts 1, 2, 4, and 6 identified visual inspections of the transformer case as one of the evaluation criteria. A good rating would result if a visual inspection of the case showed no signs of corrosion. A poor rating, on the other hand, results from a case which is severely corroded and leaking. This description resulted in the following linear equation:

$$TC1 = 50 - [(\#\ Fair\ Xformer) + 2*(\#\ Poor\ Xformer)] \quad (37)$$

where

Fair Xformer = number of distribution transformers, rated 100 KVA or higher, where minor corrosion is evident but transformer case is not leaking

Poor Xformer = number of distribution transformers, rated 100 KVA or higher, where extensive corrosion is evident or transformer case is leaking

Age was also considered as a parameter to determine the condition of distribution transformers. According to Expert 6, a transformer is in fair condition if it is between 15 and 25 years old. Transformers older than 25 years should be rated poor. The following linear equation resulted:

$$TC2 = 50 - (Age) \tag{38}$$

where

Age = Average age of distribution transformers, in years

The condition index for the distribution transformer network case, CI(DTC), is then calculated by combining equations (37) and (38) to yield the following equation:

$$CI(DTC) = TC1 + TC2 \tag{39}$$

<u>Characteristics</u>. According to Expert 6, transformer characteristics can best be evaluated by the amount and duration of transformer loading. A transformer is in good condition if it is never overloaded. A rating of fair would result if a transformer were overloaded minimally, between one and four hours per day. Finally, a rating of poor would result from excessive overloading, between eight and ten hours per day. Taking into account the number of transformers involved generated the following linear equation:

$$CI(DTCH) = 100 - [2*(\#\ \text{min overload}) + 4*(\#\ \text{max overload})] \tag{40}$$

where

min overload = number of distribution transformers, rated 100 KVA or higher, which are overloaded between 1 and 5 hours per day

max overload = number of distribution transformers, rated 100 KVA or higher, which are overloaded 6 or more hours per day

<u>Protective Devices</u>. In order for a transformer to be in good condition, it must be properly protected in a number of ways. Protective devices include fuses, lightning arrestors, and grounding mechanisms. Expert 6 recommends fuses be rated for 150% - 250% of transformer full load current. Fuses rated higher than 300% of full load current are inadequate. Expert 1 states that a transformer is in fair condition if it is properly fused and has good grounding, but has inadequate lightning protection. These criteria yielded the following linear equation describing the condition index for the distribution transformer network, CI(DTPD):

$$CI(DTPD) = 100 - [2*(\#\ Fair\ Prot) + 4*(\#\ Poor\ Prot)] \qquad (41)$$

where

Fair Prot = number of distribution transformers, rated 100 KVA or higher, which have inadequate lightning protection but are properly fused and grounded; or which have fuses rated for 250% of full load current

Poor Prot = number of distribution transformers, rated 100 KVA or higher, which have fuses rated higher than 300% of full load current; or which have inadequate grounding

Combining equations (34), (35), (36), (39), (40), and (41) with the weighting factors contained in Appendix D, Table 18, resulted in the following equation for the distribution transformer network condition index, CI(Transformers):

$$CI(Transformers) = 0.26*CI(DTIM) + 0.20*CI(DTC) + 0.24*CI(DTCH) + 0.30*CI(DTPD) \qquad (42)$$

Switchgear. Switchgear operate in the electrical distribution system in the same manner as bypass switches operate in the substation. The difference lies in the scale involved. Bypass switches are a small part of a subsystem whereas switchgear can be considered a subsystem in themselves. Switchgear can be broken into three critical components: switch, case, and relays. The condition index for each of the critical components is calculated below, followed by the overall condition index for switchgear, CI(Switchgear).

Switch. Experts 8 and 10 recommend a visual inspection of the switch mechanism and contacts. Evaluation can be made based on switch operability and amount of corrosion. Poor condition is indicated by extreme difficulty in operation, or by corroded, pitted, or burned contacts. According to Expert 8, the switchgear subsystem is in fair condition if no more than 5% to 10% of the switches evaluated are in poor condition. Using the percentages as endpoints for the fair criteria yielded the following linear equation:

$$CI(SS) = 100 - [2*(\%\text{ poor switches})] \qquad (43)$$

where

% poor switches = percentage of evaluated switches which were extremely difficult to operate or which showed excessive corrosion of the contacts

Case. The condition of the case is also determined through visual inspection. Expert 3 recommended inspecting seams, doors, and foundation for signs of deterioration and corrosion. Good cases will show no signs of deterioration. A case is considered fair if slight

corrosion appears at the seams, doors, and foundation, while a poor rating is given for excessive corrosion. This evaluation criteria translated into the following linear equation:

$$CI(SC) = 100 - [(\%\ \text{rated fair}) + 2*(\%\ \text{rated poor})] \quad (44)$$

where

% rated fair = percentage of evaluated switchgear cases which showed minor signs of corrosion or deterioration

% rated poor = percentage of evaluated switchgear cases which showed excessive deterioration or corrosion

<u>Relays</u>. The final critical component for the switchgear was identified as the relays. The switchgear relays are evaluated in the same manner as the substation relays discussed above. Though there are numerous relays involved, the evaluation criteria suggested by Expert 1 eliminated the need to develop a linear equation using the numbers of components assigned each rating, as established for switchgear cases and switches earlier. The condition criteria depend on how the relays are tested and calibrated by maintenance personnel, and whether or not results of a short circuit analysis/coordination study were used to set the relays. The following discrete equations were used to assign a value to the condition index for switchgear relays, CI(SSR):

CI(SSR) = 100 If relays are set according to short circuit analysis and coordination study using primary current inspection (45)

CI(SSR) = 75 If relays are set according to short circuit analysis and coordination study using secondary current inspection (46)

CI(SSR) = 50 Relays are tested and reset to original settings without the aid of a short circuit analysis and coordination study (47)

The condition index for switchgear, CI(Switchgear), is finally calculated by combining equations (43) through (47) with the weighting factors from Appendix D, Table 19:

$$CI(Switchgear) = 0.40*CI(SS) + 0.28*CI(SC) + 0.32*CI(SSR) \quad (48)$$

Maintenance and Inspection. The condition of the maintenance and inspection key system factor can be evaluated based on four critical subfactors: maintenance plan, training level, manning and experience, and proper equipment. The condition index for each of these critical subfactors is calculated below, followed by the overall condition index for the maintenance and inspection system factor, CI(Maint).

Maintenance Plan. The first critical subfactor affecting maintenance and inspection is the availability of a good maintenance plan. Experts 3 and 4 both recommended checking the plan for completeness and scheduled accomplishment. The plan must be thorough and in use to receive a good rating. If a general plan exists, with no specific detail or breakdown of requirements, and is in use, a rating of fair can be given. If the plan is incomplete or not scheduled for accomplishment, then this area receives a poor rating. Putting this criteria summary into equation form yielded the following set of discrete equations:

CI(MIMP) = 100 If a thorough maintenance and inspection plan is fully updated and in regular use (49)

CI(MIMP) = 70	If a general maintenance and inspection plan is in regular use (no specific breakdown of requirements)	(50)
CI(MIMP) = 40	No maintenance and inspection plan exists, or existing plan is not used	(51)

Training Level. The level of training shop technicians receive, and the resulting proficiency, are important in all organizations. Experts 1 and 2 identified training levels and further recommended adequate in-house workloads be maintained to ensure proficiency levels of trained workers. The resulting set of discrete equations was:

CI(MITL) = 100	If all personnel are fully trained and sufficient in-house work is accomplished to maintain proficiency levels. Technicians should attend training every two years	(52)
CI(MITL) = 70	If 75% of personnel are trained and sufficient in-house work exists to maintain proficiency of trained personnel and provide OJT for untrained personnel. Technicians attend training/seminar every three years	(53)
CI(MITL) = 40	Personnel are not fully trained and little in-house work available to gain proficiency. No formal training program established	(54)

Manning/Experience. Good maintenance cannot be performed without sufficient, experienced personnel. Expert 2 recommended comparing available manpower against authorized manning and workload history. The available manning should be able to complete all required repairs and service calls with extra time available for routine maintenance. The equations which describe the condition index for manning/experience are listed below:

CI(MIME) = 100	If adequate, experienced manning exists to accomplish all required repairs, service calls, and routine maintenance	(55)
CI(MIME) = 70	If shop is not capable of major repair tasking due to insufficient or inexperienced manning	(56)
CI(MIME) = 40	If shop is unable to accomplish routine maintenance and repair due to lack of manpower or experience	(57)

<u>Proper Equipment</u>. The final critical subfactor for maintenance and inspection is proper equipment. According to Expert 2, a shop cannot perform necessary maintenance and repair work if proper equipment is unavailable or if existing equipment is poorly maintained. The condition index for this critical subfactor is described by the following set of discrete equations:

CI(MIPE) = 100	If shop has all necessary tools and equipment to perform routine maintenance and repair work. All tools and equipment kept in good repair	(58)
CI(MIPE) = 70	If shop has a majority of the tools and equipment necessary for routine maintenance and repair work. All available tools and equipment well maintained	(59)
CI(MIPE) = 40	Shop is poorly equipped or existing tools and equipment are poorly maintained	(60)

The condition index for maintenance and inspection, CI(Maint), is derived by combining equations (49) through (60) with the weighting factors from Appendix D, Table 21. The resulting equation was:

$$\mathrm{CI(Maint)} = 0.25*\mathrm{CI(MIMP)} + 0.27*\mathrm{CI(MITL)} + 0.28*\mathrm{CI(MIME)} + 0.20*\mathrm{CI(MIPE)} \qquad (61)$$

Diagnostic Tools. The condition of the diagnostic tools system factor can be determined by evaluating several of the tools commonly available: coordination studies, as-built drawings and distribution maps, thermographic surveys, and manufacturers' instruction manuals. The condition index for each of these critical subfactors is detailed below, followed by the condition index for the diagnostic tools system factor, CI(Tools).

Coordination Study. Expert 1 recommends checking to see if short circuit analysis, coordination study, and load flow analysis are all available and current. According to Expert 3, the coordination study should be thorough and complete. However, the best study is worthless if not implemented. The discrete equations resulting from the evaluation criteria were:

CI(DTCS) = 100	If short circuit analysis and coordination study are current and the base electrical distribution system is coordinated in accordance with study's recommendations	(62)
CI(DTCS) = 70	If short circuit analysis and coordination study are several years old and have not been updated to reflect current system configuration	(63)
CI(DTCS) = 40	If no short circuit analysis or coordination study exist for current electrical distribution system	(64)

Drawings/Maps. The condition index for record and as-built drawings and distribution maps can be determined from the level of detail contained in the maps and from the time required to make updates. Evaluation criteria from Expert 2 was used to derive the following discrete equations:

DM1 = 50	If shop has accurate, up-to-date distribution maps with color coding of feeder circuits and all switch locations marked	(65)
DM1 = 35	If distribution maps are accurate and marked up, but do not contain all necessary information	(66)
DM1 = 20	If distribution maps are not current	(67)
DM2 = 50	If record and as-built drawings are accurate and are updated within six months after any changes	(68)
DM2 = 35	If record and as-built drawings are accurate and are updated within one year after any changes	(69)
DM2 = 20	If record and as-built drawings are inaccurate or if updates require more than one year to complete	(70)

$$CI(DTDM) = DM1 + DM2 \tag{71}$$

Thermographic Survey. A thermographic survey is extremely useful in locating trouble spots in an electrical distribution system since failing components or corroded terminations increase resistance at the point of failure. An increase in resistance leads to a corresponding increase in temperature which is easily seen in any infrared scan (30). The condition index for thermographic surveys is easy to evaluate; a base eitner has or does not have a current (less than 1 year old) survey. This is quantitatively depicted by the following two equations:

CI(DTTS) = 100	If a current thermographic survey is available	(72)
CI(DTTS) = 50	If a current thermographic survey is not available	(73)

Manufacturer's Instructions. The final critical subfactor identified under diagnostic tools is availability of manufacturers' instruction manuals for major electrical distribution system components. According to Expert 4, these manuals are necessary to aid in solving component unique problems. As in the case of thermographic surveys, either the shop has the manuals, or it does not have the manuals. This relationship is depicted by the following equations:

CI(DTMI) = 100	If shop has manufacturers' manuals for all major system components	(74)
CI(DTMI) = 50	If shop does not have manufacturers' manuals for all major system components	(75)

The condition index for diagnostic tools, CI(Tools), is defined by combining equations (62), (63), (6 4) and (71) through (75) with the weighting factors from Appendix D, Table 22, to yield:

$$CI(Tools) = 0.29*CI(DTCS) + 0.29*CI(DTDM) + 0.22*CI(DTTS) + 0.20*CI(DTMI) \qquad (76)$$

Outage Records. Most experts agreed that power outage records could be used to help determine the condition index for the overall electrical distribution system. The recommended areas of evaluation include frequency, cause, duration, and extent of power outages. However, no condition or evaluation criteria was given by the experts responding to the Delphi survey. Therefore, the equations developed for the following critical system subfactors are the result of technical research and interviews with other experts (14; 39).

Frequency. According to one electrical engineer, a typical base will experience approximately five power outages during the course

of one year (39). Power outages may result from natural occurrences such as lightning strikes, or from component failure. No dist' ·tion for cause should be made since good system condition should reduce the impact of all power outages on the overall system (39). This subfactor would be considered good if no more than four power outages occur within one year. If the base experiences five to eight power outages this area should rate fair. Finally, a rating of poor would result if more than eight power outages were recorded during the past year. The above criteria translated to the following linear equation:

$$CI(ORF) = 100 - [5*(\# \text{ of outages})] \tag{77}$$

where
# of outages = total number of power outages experienced by the base in the past 12 months

Cause. The next critical subfactor affecting power outages was cause. Several experts agreed that this was the most important item to look at when considering power outages. Appendices A through E of the IEEE Gold Book detail expected values for component failure (reliability analysis) for major individual components in an electrical distribution system (24). This data, coupled with interviews of additional engineers, resulted in the following linear equation describing the condition index for power outage cause, CI(ORC):

$$CI(ORC) = 100 - [15*(\# \text{ component outages})] \tag{78}$$

where
component outages = number of power outages experienced as a direct result of component failure during the past 12 months

Duration/Extent. The final subfactor for power outages concerns the duration and extent of the power outage. An analysis of the duration of the power outages coupled with the percentage of the base affected by the outage is necessary to arrive at the condition and evaluation criteria. Power outages of greater duration are usually the result of poor system condition or improper maintenance (39). The extent of a power outage is also an indicator of the condition of a system because a system which is in good condition is better able to minimize the extent of the outage through various techniques (29). The following discrete equations were developed to model the condition index for power outage duration/extent, CI(ORD):

CI(ORD) = 100	If no power outages during past 12 months	(79)
CI(ORD) = 85	If duration of worst outage was less than 2 hours OR if extent of outage was less than 25% of base	(80)
CI(ORD) = 70	If duration of worst outage was less than 4 hours AND extent was less than 50% of base	(81)
CI(ORD) = 50	If duration of worst outage was greater than 4 hours or extent greater than 50% of base	(82)

The condition index for outage records, CI(Outage), was defined by combining equations (77) through (82) with the weighting factors from Appendix D, Table 23, to yield:

$$CI(Outage) = 0.36*CI(ORF) + 0.39*CI(ORC) + 0.25*CI(ORD) \qquad (83)$$

V. Expert System Development

Overview

As stated earlier, an expert system is intended to model the thinking and model solving capabilities of a human expert in his or her field of expertise (28:1). The expert system accomplishes this task by representing the acquired knowledge in such a way that the program's inference mechanism, a part of the expert system shell, can form a solid line of reasoning from the beginning of the problem until the final goal is achieved.

Expert system shells typically contain an inference engine and a language used to represent the acquired knowledge. They must also contain required functions for constructing a user interface; a method to incorporate additional user knowledge into the existing knowledge base. In addition, expert system shells usually contain program development aids to enhance editing, tracing, and debugging capabilities (3:Volume 1, 3). Figure 2 shows the typical architecture of a rule-based expert system (3:8).

A rule-based expert system is characterized by a separate, explicit set of rules used to represent the knowledge. By separating the "knowledge" from the general inference structure, modifications or expansions to the rule-base are much easier than a typical procedural language program (9). An added benefit is that a well designed expert system can increase the efficiency of the problem solving process by aiding in the decision-making process. This is especially true of rule-

based knowledge representations which follow logical and empirical "rules-of-thumb" (9:Summary,1)

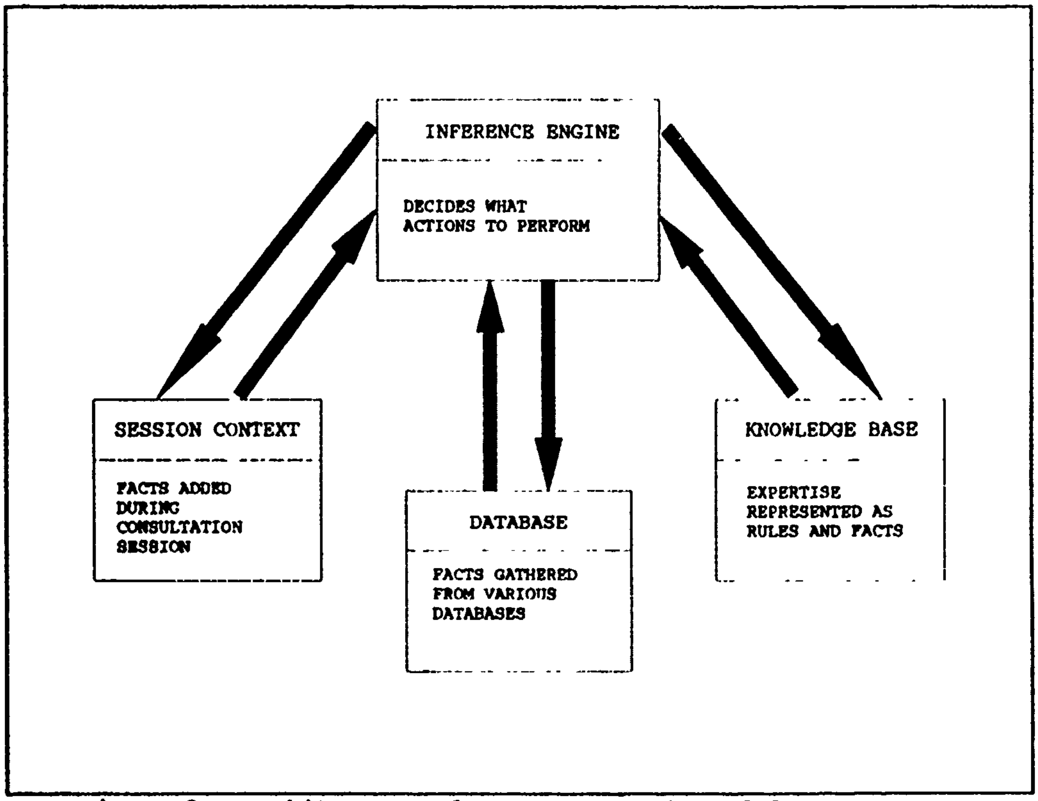

Figure 2. Architecture of an Expert System (3:8)

The purpose of this chapter is to present the methodology used to incorporate the acquired knowledge into a usable rule-based expert system. It was important that the expert system be developed in as general a framework as possible for several reasons. First, the system must be capable of operating over a fairly broad range of electrical distribution systems. Second, extensions of the current solution approach should be as straightforward as possible. Finally, general rules simplify program development since fewer rules are required to govern a specific class of problems (9:Sec 2,1-4).

Selection of Expert System Shell

Three expert system shells were reviewed for use in this research. The first, Level5-Object, developed by Information Builders, Inc., was by far the most powerful. It provides object oriented programming capabilities, supports both forward and backward chaining rules, and allows interface to numerous databases through Structured Query Language (SQL) architecture. Power, however, does not come without cost. Level5-Object requires a more advanced hardware and software platform: an Intel 80286 or compatible microprocessor with a minimum 2 megabytes of random access memory, and Microsoft's Windows 3.0 graphical user interface. The advanced platform requirements coupled with a program cost of $995.00 were the only reasons for not selecting Level5-Object for use in this research.

The other two expert system shells reviewed, the regular version of Level5, and VP-Expert by Software Publishers International, were almost identical in capabilities and requirements. Both programs will run on any IBM-compatible computer with at least 512 kilobytes of random access memory. Both support primarily backward chaining (goal-driven) rules, though forward chaining is possible. Both programs also allow interface to any dBase II or dBase III compatible databases. Level5 has the added capability of accessing FOCUS, a relational database management system developed by Information Builders, Inc., which is compatible with the WIMS database used by Air Force Civil Engineering.

The capabilities of all three expert system shells were found to be sufficient for use in developing the expert system for this thesis. VP-Expert was selected based on its lower cost, and the researcher's

prior experience with the program. It should be noted, however, that both Level5 and Level5-Object are more powerful than VP-Expert and both provide better compatibility with existing civil engineering databases.

Representing Knowledge: Development of Rules

VP-Expert can represent knowledge two ways; as facts and as rules. Facts are necessary to arrive at the end goal of the consultation. In the case of this research, the end goal is to quantify the condition of an electrical distribution system. The facts needed to reach that conclusion come from various areas: user input, database, or conclusions of rules. The rules actually contain the "expertise" of the expert system. Take as example equations (49), (50), and (51) from Chapter IV:

CI(MIMP) = 100	If a thorough maintenance and inspection plan is fully updated and in regular use	(49)
CI(MIMP) = 70	If a general maintenance and inspection plan is in regular use (no specific breakdown of requirements)	(50)
CI(MIMP) = 40	No maintenance and inspection plan exists, or existing plan is not used	(51)

These equations can be represented by the following rules:

```
RULE Maintenance Plan Good                                  (Rule 1)
      IF Maintenance_Plan_Exists = YES
         AND Plan_Extent = Thorough
         AND Plan_Use = Regular
      THEN CI(MIMP) = 100


RULE Maintenance Plan Fair or Poor                          (Rule 2)
      IF Maintenance_Plan_Exists = YES
         AND Plan_Extent = Not_Specific
         AND Plan_Use = Regular
      THEN CI(MIMP) = 70
      ELSE CI(MIMP) = 40
```

With the assumptions that (Rule 1) and (Rule 2) are the only rules in the expert system which have the condition index for maintenance plan, CI(MIMP), as the conclusion and that the rules are listed in the above order, the following sequence of events occurs during a consultation. First, the expert system establishes a goal, or subgoal, to determine the value of CI(MIMP). It searches its file of "known" facts to see if a value is there already. If the value of CI(MIMP) is not among known facts, the expert system begins searching the knowledge base for a rule which has CI(MIMP) as the conclusion. Rule 1 is the first rule to meet this condition. The expert system then evaluates the premise contained in the rule. Premise variables will be checked against known facts, or facts provided by the user if unknown, until the premise is proven true or false. If the premise proves true, the conclusion is added to the list of known facts. No other rules containing CI(MIMP) as the conclusion will be evaluated.

If the premise proves false, however, the next rule containing the goal as the conclusion is evaluated; Rule 2 in this example. The premise is checked and, if true, the conclusion is added to the list of facts. This rule also uses an ELSE clause to assign a value to the variable CI(MIMP) in the event neither of the rule premises prove true. The ELSE clause is used when no other rules contain the goal as the conclusion, and all other value which might be assigned to the premise variables result in the same outcome for the goal.

Expert System

The expert system developed using the model described in Chapter IV of this work is included at Appendix E. The program is designed

using separate modules for each key subsystem and system factor as well as a module to provide recommended areas of emphasis and a module to print the results, if desired. The chaining feature incorporated in VP-Expert allows the program to be divided into modular blocks, with each module executed as a separate program. The modular design provides two benefits. The first is easy development and testing since each module is small. The second benefit arises when the knowledge base is too large to fit into memory; chaining allows the program to be divided and executed as separate parts.

User Interface. The screen is set up with three windows. The top window is used for questions requesting user input. The bottom left window is used to track the progress of consultation by providing an indication of which module is currently executing. Furthermore, this window explains the function of each module as it executes. The bottom right window is used to keep a running summary of results for all modules as they execute.

Program Execution. The program is structured to follow the model described in Chapter IV of this work. Actions, Rules, and Statements Blocks are set off separately for each module (within Main Blocks). As you progress through each module, questions concerning that module will be asked. The expert system uses user input combined with its knowledge base to determine the condition index (CI) for each critical component or critical system factor.

Once the individual critical component or critical system subfactor CIs are known, the expert system calculates the key subsystem or key system factor CI. At the end of each module, the subsystem or

system factor CI for that module will be displayed as well as a rating based on the CI. Press any key to proceed to next module. Once all modules have executed, the overall system CI and rating are displayed. The expert system then develops a list of recommended areas for improvement by determining all of the critical components and critical system factors which received a condition index rating below 70. Both the system summary and the recommended areas for improvement can be printed, if desired.

Database Interface. One of the strong points of any expert system is its ability to access data from sources other than the user. This is especially true in cases where analysis is conducted for multiple like components. Rather than having the user answer duplicate sets of questions about a number of like items, or having the user conduct a manual data search for the information, the required information can be stored in a computer database. When the information is needed, the expert system retrieves the information directly from the computer database and analyzes the information with little or no input from the user.

Several portions of the model developed in Chapter IV of this thesis lend themselves to database applications. The distribution transformer network, in particular, requires evaluation of critical components from numerous transformers throughout the base. Each of the transformers should receive routine maintenance and inspections on a recurring basis. As the routine inspections occur, evaluations of each critical component can be made, and the information entered into a database. VP-Expert is not compatible with the WIMS database currently

used throughout Air Force Civil Engineering. Therefore, a sample database was developed using dBase III.

The sample database sets up fields for: transformer ID #, transformer size (rating), insulation condition, case condition, age, load, and protective devices condition. The transformer ID # and rating are used for identification purposes. A score of 1 to 10, with 10 being the best, is entered to represent the condition of each of the five critical components. After entering data for all inspected transformers, a dBase program is run to calculate the overall condition index for each transformer. The overall condition index is calculated using equation (42) from Chapter IV to assign weights to the critical components. The program then determines the evaluation rating for each transformer. The dBase program and sample database are attached as Appendix F.

The expert system in Appendix E uses the sample database described above to determine the condition index for the entire distribution transformer network. The expert system determines the ratio of each evaluation rating (excellent, good, fair, or poor) to the total number of transformers rated and then calculates the condition index based on these ratios.

The above sample serves to demonstrate the applicability of database access to this expert system. Further development of this database, along with development of other applicable databases, should be undertaken to enhance the operation of this expert system. Additional candidates for database applications include the distribution cable network and the switchgear subsystems.

Major Problems Encountered. Several significant problems were overcome during the development of this expert system. First was the problem with accessing a database and keeping count of the total number of like data points. Plural variables cannot be used since VP-Expert will only recognize each like response once. To solve this problem, WHILEKNOWN loops were established to read the number of occurrences of each like response and then total the number of records in the database file. These "count variables" could then be used to form ratios for each response based on the total number of responses.

The second major problem was the size of the program. VP-Expert gives no indication when memory capabilities are exceeded. The program will not execute and is returned to edit mode without any error messages. Chaining was used to solve this problem. The program is divided into six separate programs with chain calls from one to another so that all programs are executed sequentially. All necessary data is saved to a file, A:\EDSDATA, prior to chaining, and loaded into the next program immediately after chaining.

Required Expertise of User. This expert system is designed to be used by an electrical engineer, preferably the system engineer, who is familiar with his or her base's electrical distribution system. Most of the questions can be answered accurately only after careful inspection of various portions of the electrical distribution system. It is recommended that the engineer run through the expert system once or twice to familiarize himself with the questions being asked. After familiarization, the engineer should review his installation's Recurring Work Program (RWP) and associated Maintenance Action Sheets (MAS) to

verify that the required maintenance is being performed and to identify possible problem areas.

Summary

This chapter described the expert system which was developed as part of this research. The process of developing rules to represent the knowledge contained in the model was discussed along with the merits of using a rule-based system. Finally, a detailed layout of the expert system, including user interface, program execution, database access, and problems encountered was reported.

VI. Recommendations and Conclusions

Overview

The past five chapters presented research which was designed to determine if a component model could be developed to objectively quantify the condition of electrical distribution systems in the Air Force, and, if so, to evaluate the capabilities of expert system technologies for use in representing that component model. Two primary areas of investigation guided this research. The first area, development of a component model, included: identification of critical components and system subfactors, development of evaluation criteria for those critical components and system subfactors, and determination of the relative weights of each critical component or critical system subfactor to the overall distribution system. The second area, design of an expert system, encompassed: selection of a suitable expert system shell, and incorporation of the component model into the expert system structure.

This chapter proposes conclusions and recommendations based on the research objectives described above. The format consists of four sections following this overview. The first section highlights the conclusions realized for each of the primary areas of investigation. The second section describes recommendations for implementation along with validation and verification issues. The third section details three recommendations for further research which would add to and enhance the material presented in this work. Finally, the last section offers a brief summary along with the researcher's final comments.

Conclusions

The need for a quantitative rating system to qualitatively assess the condition of electrical distribution systems is well documented in the preceding chapters. This research investigated the feasibility of using component modelling, coupled with expert system technology, to provide that rating system. The conclusions arrived at after development of a component rating system, and its associated expert system, are presented below.

Use of Component Modelling Techniques. To determine the applicability of using component modelling to develop a quantitative rating system, answers to the first five investigative questions from Chapter I were required. These questions were:

1) What are the critical components and/or critical system factors which most affect the condition of the electrical distribution system?

2) Can the critical components be further broken down into subsystems and evaluated in terms of those subsystems?

3) What characteristics of each component, subsystem, or system factor can be used to describe its condition?

4) How much weight should each subsystem or subfactor have in determining the condition of its related critical component or factor?

5) How much weight should each critical component or system factor have in determining the overall system condition?

To answer these questions, the researcher conducted a Delphi survey of experts in the area of electrical distribution system design and maintenance.

The experts agreed that a quantitative rating system could be developed, and, after two rounds of the Delphi process, came to a consensus on the answers to all five questions listed above. The model

developed as a result of the experts' opinions is shown in Table 2, and fully described in Chapter IV of this thesis.

One of the strong points of this component model is its ability to distinguish between the actual physical condition of the distribution system and poor maintenance practices which may result in lower condition index (CI) scores; an ability lacking in earlier attempts at component modelling (40:77). Distinguishing between physical condition and poor maintenance practices was achieved by including system factors, which are indicators of maintenance management, as part of the overall component model.

The primary drawback to using the component model developed in Chapter IV is its complexity. The model describes the electrical distribution system in terms of 83 different equations. Many different components within the distribution system must be individually tested or inspected to provide input to these equations. Once all of the data is gathered CIs must be calculated for each critical component or critical system subfactor. Next, those CIs are combined into CIs for the key subsystems and key system factors. Finally, the CI for the electrical distribution system is calculated. If too complex or time consuming, the model will never be placed in service.

Component modelling is a valid method which can be used to accurately describe the condition of an entire system as a quantitative rating, based on the condition of individual critical components within that system. However, the resulting complexity will hamper its implementation. Encoding the model into a computer based application, as discussed below, may encourage its use by simplifying its operation.

Use of Expert System Technology. To investigate the feasibility of using expert system technology to represent the model developed in Chapter IV, answers to the final two investigative questions from Chapter I were required. These questions were:

> 6) Can expert system technology provide a suitable interface between a system engineer and the model developed in questions one through five? If so,
>
> 7) Which expert system shell will best fit within the constraints of this particular problem?

The complexity of the component model developed as part of this research made it ideal for conversion to a computer based application. Any high-level procedural computer language, such as COBOL or FORTRAN, could have been used since the model follows a logical pattern and requires only simple logic and branching statements (22). However, procedural languages require more effort in the development phase and are more difficult to modify. Therefore, the applicability of expert system technology was researched.

The expert system developed in Chapter V of this work uses a very simplistic expert system shell, VP-Expert. The program provides a good user interface coupled with a logical flow of information. The format, both in the questions asked and in the results displayed, follows the component model outlined in Figure 2. However, there were many drawbacks to using VP-Expert, primarily in the areas of program size and database access.

VP-Expert allows for a maximum single knowledge base size of 16,000 bytes, but provides the capability to chain multiple knowledge bases together for larger programs. The component model provided in this research required approximately 75,000 bytes to represent as a

knowledge base. Therefore, the expert system is broken into seven separate modules, with chaining provided between the different modules. In theory, VP-Expert allows an unlimited number of chains to occur. In practice, however, the chaining feature was inconsistent, sometimes allowing only four modules to be chained together.

Database access was also a problem. A majority of the data required for the component model is available through routine inspections performed on the individual critical components. Since many of the critical components are repetitive (i.e. transformers, switchgear, distribution cable network components, etc.), the data collected could easily be placed into a database. However, the current database in use throughout Air Force Civil Engineering is the Work Information Management System (WIMS) database. The database structure of WIMS is not compatible with the dBase III structure required by VP-Expert. Another possible source of data are the Supervisory Control and Data Acquisition (SCADA) systems currently under consideration at several of the Air Force's larger bases. These SCADA systems also present incompatibility issues with both the WIMS database and the expert system shell used for this research.

Expert system technology can provide a good interface between the user and the component rating and evaluation system described in Chapter IV of this research. However, a more powerful expert system shell should be considered. One of the expert system shells reviewed in Chapter V, Level5-Object by Information Builders, Inc., provides the power necessary to run large applications and also provides compatibility with both the WIMS and SCADA database structures.

Recommendations for Implementation

The component model and expert system developed during this research represent a "first attempt" to quantify the condition of an electrical distribution system. Field testing followed by further research and refinement are required to obtain an accurate and reliable rating system.

Validation/Verification. The component model developed from the results of the Delphi survey should be operationally tested for a minimum of two years to validate the components and weighting factors used in the model. Field testing would allow the correlation of condition index scores with actual component and system failure rates as a check to see if component condition is accurately described by the equations in the model (40:4). The only validation of the model to date came from subjective reviews of the component model by several electrical engineers (15; 29; 39).

Implementation. Implementation of the component model described in Chapter IV, and the expert system containing that model (as described in Chapter V), requires little additional work. The expert system contains the required knowledge base needed to model any typical electrical distribution system. The system engineer need only answer the questions asked by the expert system during consultation. The one area requiring additional work is database development. The database containing transformer data, shown in Appendix F, is included for demonstration purposes only, and would need to be modified to reflect the condition of the transformers at each base.

Recommendations for Further Research

The component model and expert system developed for this research should be considered as a starting point for further research. Much work is still needed to refine the model and expert system presented earlier. Additionally, refinement of the transformer database and continued development of additional databases are required to enhance the operation of the expert system. Finally, the concept of component modelling coupled with computer based applications should be applied to other facility infrastructure assets throughout the Air Force.

Refine Expert System. As stated earlier, the expert system included with this research has several limitations. Additional work is necessary to refine both the component model and the expert system developed from the component model. Validation of the component model should be accomplished through a second set of Delphi surveys as recommended by Sackman (35:24). This second set of surveys should concentrate more on the evaluation criteria of the individual components rather than identification of new components or weights (40:76)

Several more expert system shells should be evaluated, and a suitable shell selected to provide the additional capabilities needed to make this program effective. Future research could also evaluate the differences between expert system technology and high-level procedural languages, such as COBOL or FORTRAN, when applied to component modelling.

Refine/Develop Database Structures. Another point mentioned earlier was the use of databases to store the inspection results for multiple like components. A sample database for transformers was

included to demonstrate the capability of the expert system to access data from different sources. This database is not usable in its current form. The transformer database contains only information required to evaluate the condition of the transformer based on the critical components described in the model. There is no user interface to represent this data in any logical format. Additional research is required to refine this database, and to develop additional databases, to include information needed by the user as well as information required by the expert system.

Incorporate Additional F/I Assets. The electrical distribution system is one of many facility infrastructure assets requiring accurate condition assessments. This research showed that component modelling, coupled with expert system technology, is a viable solution for assessing the condition of a typical electrical distribution system. Further research should inccrporate the findings of this thesis in the development of other facility infrastructure asset rating systems. Examples of other facility infrastructure assets include: pavements, central heating plants, central chiller plants, liquid fuel distribution systems, water distribution systems, and wastewater treatment facilities.

Summary

As with any computer program, implementation simply marks the beginning of the refinement process. The expert system presented as part of this thesis is ready to begin that refinement process. The expert system and its associated component model require additional work in the areas of validation and verification of evaluation criteria,

along with refinement and development of databases needed to hold the inspection data for multiple like components. The concept of component modeling coupled with expert system technology is worthwhile and should be expanded to encompass other utility infrastructure assets throughout the Air Force. The application of this model in evaluating the condition of electrical distribution systems will serve to direct attention to those systems in greatest need of repair. Once systems are identified, proper corrective action can begin to ensure that asset's continued capability to meet current and future mission requirements.

Appendix A: First Round Delphi Package

From: AFIT/LSG 15 APR 91

Subject: Electrical Distribution System Questionnaire

To: Delphi Panel Participants

1. I wish to thank you for agreeing to participate in this AFIT sponsored survey. The purpose of this research is to aid in developing a methodology for the inspection and evaluation of electrical distribution systems. The rating system developed will help the Major Commands and individual bases locate and prevent possible problems before those problems cause catastrophic failure of the system. By using a relative numerical scale which can be compared from base to base, justification for programming actions to repair and/or replace deteriorated critical system components can be developed. By using expert system technology to apply the rating system, each base will be able to easily conduct individual inspections using their own personnel and resources.

2. You were selected to participate in this survey because your experience and proficiency in designing and/or maintaining electrical distribution systems qualifies you as an expert in this area. You will be participating with approximately 15 other experts in a process known as the "Delphi" technique.

3. The primary goal of the Delphi technique is to achieve a group consensus regarding a particular subject by using a panel of experts on

that subject. Once you have completed this survey (the first round), I will summarize all responses and return a set of all summarized responses to each participant. You will then have an opportunity to revise your responses, if desired, and to comment on the responses of the other participants. Complete confidentiality of each participant and their organizations will be maintained at all times. This confidentiality is to ensure your honest opinions by eliminating any fear of retribution or pressure from fellow experts. I anticipate only two rounds will be required to achieve consensus and complete this part of my research.

4. The first round survey is attached to this letter, along with a set of instructions and a sample response. Your prompt response to each round of the Delphi survey is necessary to ensure completion of this research within the time constraints established by AFIT. Therefore, please complete this survey within 14 days of receipt and forward to me in the enclosed return envelope. If you have any questions about this survey, I can be reached via WANG Mail at GEM OFFICIAL MAILBOX (put my name in subject block) or call AV 785-8989 and leave me a message. Thanks for taking time to share your valuable expertise.

DAVID O. PAINE, Capt, USAF
Graduate Engineering Management Student

4 Atch
1. Instructions
2. Sample Response
3. Questionnaire
4. Return Envelope

INSTRUCTIONS

1. Definition of Key Terms:

A. Electrical Distribution System: A network of components used to transport, route, and transform electrical power from its point of generation to its final point of use. This study encompasses the primary power distribution system from the point immediately after power is generated (if power is generated on base) or from the point where primary power cables first enter the confines of the base (if commercial power is used) and will continue to the point immediately after the final voltage transformation has taken place on each branch circuit.

B. Subsystem: A major division or function of the electrical distribution system which can be considered an individual system by itself. Examples of subsystems could include power transformation, substations, high-voltage cable network, etc.

C. Critical Component: Individual parts or pieces of equipment which are contained within various subsystems and which are necessary for the proper operation of that subsystem. Examples could include individual transformers, primary switchgear, high-voltage cables and connections, etc.

D. System Factor: A non-physical attribute of an electrical distribution system which has an effect on the operability, maintainability, and overall condition of that system. Examples could include system integration, system maintenance history, etc.

E. Critical Subfactors: Individual factors or attributes which impact, and can be used as a measure of, system factors. Examples could

include coordination studies, system capacity, maintenance plans, outage records, etc.

F. Weighting Factor: A number between 1 and 10 (inclusive) used to indicate the relative importance a particular subsystem, component, or factor has in regard to other subsystems, components, or factors within the electrical distribution system. A highly critical subsystem, factor, or component will receive a higher number than a less critical one.

G. Evaluation Criteria: Methods and/or rules which can be used while inspecting critical components to determine their condition or evaluating system factors/subfactors to determine their impact on system operation. Criteria could range from simple visual inspection results to more complicated analysis which include equations or simple models. In all cases, the criteria must be specific and the methods required for accomplishing the evaluation should be within the capabilities of the base squadron.

2. Specific Instructions:

A. On the first sheet of the questionnaire, please indicate whether or not your base generates its own power or purchases commercial power from the local power company. Also include the total number of years you have worked with electrical power distribution systems and whether your experience is primarily in design of systems or in maintenance of systems.

B. The survey is formatted to accept short-answer, written responses for each question. You can list up to four subsystems, five critical components for each subsystem, three system factors, and three

critical subfactors for each system factor. You may, however, choose to include more or fewer categories than shown on the preprinted questionnaire. If you feel only three subsystems are needed to accurately describe the overall system condition, then leave subsystem category "D" blank on the first page. Also leave all further questions referencing subsystem "D" blank on subsequent pages. If, on the other hand, you feel more subsystems are needed, add them to the questionnaire. You may wish to attach additional pages to those provided. Please label all additional subsystems, critical components, system factors, and critical subfactors in a manner consistent with the rest of the questionnaire.

3. General Comments:

A. A partial sample response is included in this package as a guide for the format of your responses. There are no restrictions on the weighting factors for any item (the numbers do not have to total to any specific amount) except that, for simplicity, each factor should be an integer between 1 and 10. The weighting factors for any item are relative (i.e. a "10" is twice as important as a "5"). If you list, as an example, four critical components for a particular subsystem and weight each one a "10", this means each of the critical components has equal importance (the same would be true if all were weighted "5"). Therefore, it's best to begin by assigning a value of "10" to the item within each category you feel is the most important item. You can then assign proportionately lower weighting factors to items of lessor importance.

B. Each and every component within the electrical distribution system is needed for proper operation. So, when selecting the most important components, please consider the following: Availability of spare parts, potential to cause a full or partial power outage, potential for reliability or performance deterioration, and overall effect on life span of distribution system.

C. Your participation and accurate responses are critical to the success of this research. Please remember that no thought or opinion is too trivial to be included. An insignificant item to you might trigger a "brainstorm" in one of the other experts during the next round of questioning.

THANKS FOR YOUR PARTICIPATION !!

SAMPLE

ELECTRICAL DISTRIBUTION SYSTEM QUESTIONNAIRE

1. What is the source of electrical power at your base? (Circle one)

   A. Power generated on base.

   B. Power purchased from local utility company.

2. How many years have you been working with electrical distribution systems?

   ____10____

3. What is your primary area of expertise with electrical distribution systems? (Circle one)

   A. Design

   B. Maintenance

4. In your opinion, what are the most important subsystems within the electrical distribution system and what weighting factor would you assign to each subsystem? (You may list more or less than four subsystems. If additional subsystems are listed, please attach additional sheets of paper.)

SUBSYSTEM	WEIGHTING FACTOR
A: Power Transformation	A: 10
B: High-Voltage Cable Network	B: 6
C: Substation	C: 8
D: Switchgear	D: 6

SAMPLE

SAMPLE

5. For <u>SUBSYSTEM A</u> list its most critical components and their weighting factors. (More or less than five may be listed.)

COMPONENT	WEIGHTING FACTOR
A1: Case	A1: 5
A2: Core	A2: 9
A3: Bushings	A3: 3
A4: Insulation	A4: 7
A5:	A5:

6. For each component in <u>SUBSYSTEM A</u>, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

<u>COMPONENT A1</u>:

Criteria: Visual inspection of transformer to determine condition

Excellent: Case shows no signs of corrosion or deterioration

Fair: Case shows signs of corrosion at seams and joints - No leaking insulation

Poor: Case is very deteriorated - extensive corrosion throughout - minor leaks of insulation material

SAMPLE

13. In your opinion, what are the most important SYSTEM FACTORS within the electrical distribution system and what weighting factor would you assign to each SYSTEM FACTOR? (More or less than three may be listed.)

SYSTEM FACTOR	WEIGHTING FACTOR
A: System Maintenance	A: 10
B: System Integration	B: 5
C: System Capacity vs Demand/Growth	C: 7

14. For SYSTEM FACTOR A list its most critical SUBFACTORS and their weighting factors. (More or less than three may be listed.)

SUBFACTOR FACTOR	WEIGHTING
A1: Maintenance Plan / RWP	A1: 10
A2: Thermographic Survey Completed	A2: 4
A3: Power Outage History	A3: 6

SAMPLE

15. For each SUBFACTOR in SYSTEM FACTOR A, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

SUBFACTOR A1:

Criteria: Determine if maintenance plan exists, and is followed, to perform routine maintenance under RWP

Excellent: Extensive plan exists and is followed. Plan breaks out individual components and required actions.

Fair: Good plan exists and is followed at least 75% of time.

Poor: No plan exists or existing plan is not used.

ELECTRICAL DISTRIBUTION SYSTEM QUESTIONNAIRE

1. What is the source of electrical power at your base? (Circle one)

   A. Power generated on base.

   B. Power purchased from local utility company.

2. How many years have you been working with electrical distribution systems?

   ____

3. What is your primary area of expertise with electrical distribution systems? (Circle one)

   A. Design

   B. Maintenance

4. In your opinion, what are the most important subsystems within the electrical distribution system and what weighting factor would you assign to each subsystem? (You may list more or less than four subsystems. If additional subsystems are listed, please attach additional sheets of paper.)

SUBSYSTEM	WEIGHTING FACTOR
A: ____________________ ____________________	A: ________
B: ____________________ ____________________	B: ________
C: ____________________ ____________________	C: ________
D: ____________________ ____________________	D: ________

5. For SUBSYSTEM A list its most critical components and their weighting factors. (More or less than five may be listed.)

COMPONENT	WEIGHTING FACTOR
A1: ______________________	A1: ________
______________________	
A2: ______________________	A2: ________
______________________	
A3: ______________________	A3: ________
______________________	
A4: ______________________	A4: ________
______________________	
A5: ______________________	A5: ________
______________________	

6. For each component in SUBSYSTEM A, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

COMPONENT A1:

Criteria: ____

____

Excellent: ____

____

Fair: ____

____

Poor: ____

____

SUBSYSTEM A components (continued)

COMPONENT A2:

Criteria: ____________________

____

Excellent: ____________________

____

Fair: ____________________

____

Poor: ____________________

____

COMPONENT A3:

Criteria: ____________________

____

Excellent: ____________________

____

Fair: ____________________

____

Poor: ____________________

____

SUBSYSTEM A components (continued)

COMPONENT A4:

Criteria:____

____

Excellent:____

____

Fair:____

____

Poor:____

____

COMPONENT A5:

Criteria:____

____

Excellent:____

____

Fair:____

____

Poor:____

____

7. For SUBSYSTEM B list its most critical components and their weighting factors. (More or less than five may be listed.)

COMPONENT	WEIGHTING FACTOR
B1: ______________________	B1: ________
______________________	
B2: ______________________	B2: ________
______________________	
B3: ______________________	B3: ________
______________________	
B4: ______________________	B4: ________
______________________	
B5: ______________________	B5: ________
______________________	

8. For each component in SUBSYSTEM B, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

COMPONENT B1:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

SUBSYSTEM B components (continued)

<u>COMPONENT B2</u>:

Criteria:____

____

Excellent:______________________________________

____

Fair: ____

____

Poor:____

____

<u>COMPONENT B3</u>:

Criteria:____

____

Excellent:______________________________________

____

Fair:____

____

Poor:____

____

SUBSYSTEM B components (continued)

COMPONENT B4:

Criteria:______________________________

____

Excellent:______________________________

____

Fair:______________________________

____

Poor:______________________________

____

COMPONENT B5:

Criteria:______________________________

____

Excellent:______________________________

____

Fair:______________________________

____

Poor:______________________________

____

9. For SUBSYSTEM C list its most critical components and their weighting factors. (More or less than five may be listed.)

COMPONENT	WEIGHTING FACTOR
C1: ____________________	C1: ________
C2: ____________________	C2: ________
C3: ____________________	C3: ________
C4: ____________________	C4: ________
C5: ____________________	C5: ________

10. For each component in SUBSYSTEM C, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

COMPONENT C1:

Criteria:____________________

Excellent:____________________

Fair:____________________

Poor:____________________

SUBSYSTEM C components (continued)

<u>COMPONENT C2</u>:

Criteria:____

____

Excellent:____

____

Fair:____

____

Poor:____

____

<u>COMPONENT C3</u>:

Criteria:____

____

Excellent:____

____

Fair:____

____

Poor:____

____

SUBSYSTEM C components (continued)

COMPONENT C4:

Criteria:______________________________

Excellent:______________________________

Fair:______________________________

Poor:______________________________

COMPONENT C5:

Criteria:______________________________

Excellent:______________________________

Fair:______________________________

Poor:______________________________

11. For SUBSYSTEM D list its most critical components and their weighting factors. (More or less than five may be listed.)

COMPONENT	WEIGHTING FACTOR
D1: ____________	D1: ______
D2: ____________	D2: ______
D3: ____________	D3: ______
D4: ____________	D4: ______
D5: ____________	D5: ______

12. For each component in SUBSYSTEM D. list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

COMPONENT D1:

Criteria: ____________

Excellent: ____________

Fair: ____________

Poor: ____________

SUBSYSTEM D components (continued)

<u>COMPONENT D2</u>:

Criteria: ____

____

Excellent: ______________________________________

____

Fair: ____

____

Poor: ____

____

<u>COMPONENT D3</u>:

Criteria: ____

____

Excellent: ______________________________________

____

Fair: ____

____

Poor: ____

____

SUBSYSTEM D components (continued)

COMPONENT D4:

Criteria:____

Excellent:___________________________________

Fair:______________________________________

Poor:______________________________________

COMPONENT D5:

Criteria:____

Excellent:___________________________________

Fair:______________________________________

Poor:______________________________________

13. In your opinion, what are the most important SYSTEM FACTORS within the electrical distribution system and what weighting factor would you assign to each SYSTEM FACTOR? (More or less than three may be listed.)

SYSTEM FACTOR	WEIGHTING FACTOR
A: ______________________	A: ________
______________________	
B: ______________________	B: ________
______________________	
C: ______________________	C: ________
______________________	

14. For SYSTEM FACTOR A list its most critical SUBFACTORS and their weighting factors. (More or less than three may be listed.)

SUBFACTOR	WEIGHTING FACTOR
A1: ______________________	A1: ________
______________________	
A2: ______________________	A2: ________
______________________	
A3: ______________________	A3: ________
______________________	

15. For each SUBFACTOR in SYSTEM FACTOR A, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

SUBFACTOR A1:

Criteria: ____

____

Excellent: ____

____

Fair: ____

____

Poor: ____

____

SUBFACTOR A2:

Criteria: ____

____

Excellent: ____

____

Fair: ____

____

Poor: ____

____

SYSTEM FACTOR A (continued)

SUBFACTOR A3:

Criteria:____

Excellent:____

Fair:____

Poor:____

16. For SYSTEM FACTOR B list its most critical SUBFACTORS and their weighting factors. (More or less than three may be listed.)

SUBFACTOR	WEIGHTING FACTOR
B1: ________________	B1: ________
B2: ________________	B2: ________
B3: ________________	B3: ________

SYSTEM FACTOR B (continued)

17. For each SUBFACTOR in <u>SYSTEM FACTOR B</u>, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

<u>SUBFACTOR B1</u>:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

<u>SUBFACTOR B2</u>:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

SYSTEM FACTOR B (continued)

<u>SUBFACTOR B3</u>:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

18. For <u>SYSTEM FACTOR C</u> list its most critical SUBFACTORS and their weighting factors. (More or less than three may be listed.)

<u>SUBFACTOR</u>	<u>WEIGHTING FACTOR</u>
C1: ______________________	C1: __________
C2: ______________________	C2: __________
C3: ______________________	C3: __________

SYSTEM FACTOR C (continued)

19. For each SUBFACTOR in SYSTEM FACTOR C, list the evaluation criteria you would use to establish the condition of each component. Assign a definition for excellent, fair, and poor condition for each criteria.

SUBFACTOR C1:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

SUBFACTOR C2:

Criteria: ______________________________

____

Excellent: ______________________________

____

Fair: ______________________________

____

Poor: ______________________________

____

SYSTEM FACTOR C (continued)

<u>SUBFACTOR C3</u>:

Criteria:____

____

Excellent:____

____

Fair:____

____

Poor:____

____

Appendix B: Second Round Delphi Package

From: AFIT/LSG 13 June 91

Subject: Electrical Distribution System Questionnaire

To: Delphi Panel Participants

1. I wish to thank you for agreeing to participate in this AFIT sponsored survey. As a reminder, the purpose of this research is to aid in developing a methodology for the inspection and evaluation of electrical distribution systems. The rating system developed will help the Major Commands and individual bases locate and prevent possible problems before those problems cause catastrophic failure of the system. By using a relative numerical scale which can be compared from base to base, justification for programming actions to repair and/or replace deteriorated critical system components can be developed. By using expert system technology to apply the rating system, each base will be able to easily conduct individual inspections using their own personnel and resources.

2. I'm very pleased with the first round results. The experts responding to the first round questionnaire provided me a wealth of information on various critical components and their related weighting factors and inspection criterion. This second round of questioning is formatted differently and, due to the great amount of effort exerted on the first round, will require much less time to complete. I've only summarized the results for critical components, system factors, and their associated weights. I will send you a summary of the inspection criterion at a later date, after I've had adequate time to analyze those

responses. This second round survey, however, will be the final round of actual questioning.

3. The primary goal of the Delphi technique is to achieve a group consensus regarding a particular subject by using a panel of experts on that subject. I have summarized all first round responses related to primary subsystems, critical components, and key system factors. This will allow you an opportunity to revise your responses, if desired, and to comment on the responses of the other participants. Complete confidentiality of each participant and their organizations will be maintained at all times. This confidentiality is to ensure your honest opinions by eliminating any fear of retribution or pressure from fellow experts.

4. The second round survey is attached to this letter, along with a set of instructions and a sample response. Your prompt response to this final round of the Delphi survey is critical if this research is to be completed within the time constraints established by AFIT. Therefore, please complete this survey within 14 days of receipt and forward to me in the enclosed return envelope. If you have any questions about this survey, I can be reached via WANG Mail at GEM OFFICIAL MAILBOX (put my name in subject block) or call AV 785-8989 and leave me a message. Thanks for taking time to share your valuable expertise.

DAVID O. PAINE, Capt, USAF

Graduate Engineering Management Student

4 Atch

1. Instructions
2. Sample Response
3. Questionnaire
4. Return Envelope

INSTRUCTIONS

1. Overview of Round Two:

A. This questionnaire summarizes all responding experts' opinions on key electrical distribution subsystems and key factors along with their associated critical components and critical subfactors. The summary of systems and components were grouped according to the consensus of participating experts, therefore, some experts will find a particular response may have been included in a different subsystem or key factor category than originally indicated. A summary of responses for inspection criterion will be forwarded for your review at a later date. If you were unable to respond to the first round questionnaire you are still encouraged to answer this round. Everyone's opinion is important to the success of this research.

B. The summary includes information on the total number of experts who identified a particular subsystem, factor, or critical component. It also gives a listing of identified items and the average of the weighting factors assigned by various experts in terms of a 1-10 scale. The only responses required for this survey are the assigning of weights, on a scale of 1 -10, for the subsystems, key factors, and critical components you think are most important in each category.

2. Specific Instructions: You are asked to complete all parts of this survey regardless of subsystems or key factors you identified in the first round survey. The survey first details the six subsystems identified by experts. Please weigh at least four of these subsystems. The next six sections list the critical components identifies in each of

the subsystems. Please weigh no more than the maximum number of choices allowed under each subsystem heading (as indicated in the right-hand column). You may weigh less than the maximum if desired. Following the critical component sections is the listing of four key system factors, of which at least three must be weighed. The final four sections list the subfactors identified for each key system factor along with the maximum number of subfactors which can be weighed. Please feel free to pencil in additional components or subfactors if desired.

3. General Comments:

A. A partial sample response is included as a guide. There are no restrictions on the weights assigned to any response except that, for simplicity, each number should be an integer between 1 and 10. The weights for any item are relative, meaning that a "5" is half as important as a "10". If, for example, you assign the same number to all components in a category, this means you consider each item to have equal importance, regardless of the number assigned. Therefore, its best to begin assigning weights for each category by first picking the most important item and assigning it a "10" and then assigning proportionately lower weights to items with lesser importance.

B. Your participation is key to the success of this research. I greatly appreciate the effort put into the first round responses and look forward to seeing your opinions in this second and final round of questions.

THANKS AGAIN FOR YOUR PARTICIPATION !!!

SAMPLE

Electrical Distribution System
Primary Distribution Cable Network
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 6 Critical Components
8	Conductors (Physical Characteristics)	8.5	10
7	Supporting Structure (Poles, Conduit, Manholes, and etc.)	7.7	7
6	Insulation (Type, Characteristics)	8.3	7
6	Other Components (Switches, Sectionalizers, Cutouts, Reclosures, Potheads)	6.7	
4	Terminations	8.3	4
2	Ampacity/Loading	8.0	5
1	Lightning Arrestors	6.0	

This section combines ratings given for both underground and overhead primary distribution networks.

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

SAMPLE

ROUND TWO DELPHI QUESTIONNAIRE

Electrical Distribution System
Key Subsystems

# of Experts Selecting Subsystem	Key Subsystem	Average Weight Factor	Weight at least 4 Subsystems
10	Substation (including main transformers if applicable)	9.4	________
10	Primary Distribution Cable Network (High Voltage)	7.9	________
8	Distribution Transformer Network	6.9	________
5	Switchgear	6.8	________
2	Secondary Distribution Cable Network (Low/ Medium Voltage)	6.0	________
1	Protective Devices	8.0	________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Substation Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 6 Critical Components
7	Breakers	8.3	________
7	Bypass Switches	6.6	________
4	Primary Transformer (If present)	9.3	________
3	Busswork with Supporting Insulators	8.3	________
3	Lightning Arrestors	5.7	________
2	Main Switch	10.0	________
2	Substation Structure	6.5	________
1	Relays	9.0	________
1	Fault Interrupter Switches	6.0	________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Primary Distribution Cable Network
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Facto	Weight no more than 6 Critical Components
8	Conductors (Physical Characteristics)	8.5	________
7	Supporting Structure (Poles, Conduit, Manholes, and etc.)	7.7	________
6	Insulation (Type, Characteristics)	8.3	________
6	Other Components (Switches, Sectionalizers, Cutouts, Reclosures, Potheads)	6.7	________
4	Terminations	8.3	________
2	Ampacity/Loading	8.0	________
1	Lightning Arrestors	6.0	________

This section combines ratings given for both underground and overhead primary distribution networks.

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Distribution Transformer Network
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 6 Critical Components
5	Insulation Medium	9.2	________
5	Case (Condition)	7.6	________
3	Transformer Characteristics	9.7	________
3	Protective Devices	9.0	________
1	Lightning Arrestors	6.0	________
1	Load Tap Changers	5.0	________
1	Regulators	8.0	________
1	Bushings	10.0	________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Switchgear
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 3 Critical Components
4	Switch (Physical Characteristics)	9.3	________
3	Case (Physical Condition)	5.7	________
2	Relays	8.0	________

Electrical Distribution System
Secondary (LV) Distribution Cable Network
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 3 Critical Components
2	Conductors (Physical Characteristics)	9.0	________
1	Supporting Structure (Poles, Conduit, Manholes, and etc.)	8.0	________
1	Insulation (Type, Characteristics)	10.0	________
1	Other Components (Switches, Sectionalizers, Cutouts, Reclosures, Potheads)	5.0	________

This section combines ratings given for both underground and overhead secondary distribution networks. Most experts did not distinguish between primary and secondary distribution networks -- those responses are included in the primary distribution network section (see above).

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Protective Devices
Critical Components

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor	Weight no more than 3 Critical Components
1	Coordination Study Implemented	10.0	______
1	Coordination Study Current	9.0	______
1	Devices (Type, Characteristics)	9.0	______
1	Backfeed Capability (to Reduce Outage Area)	5.0	______

Some of the critical components listed in this section were also considered system factors (i.e. coordination study) by other experts, therefore, they have also been included in the critical subfactors section.

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Key System Factors

# of Experts Selecting System Factor	Key System Factor	Average Weight Factor	Weight at least 3 Key Factors
8	Maintenance and Inspection of System	9.4	__________
7	Diagnostic Tools (SCADA, Distribution Maps, Coordination Studies)	7.1	__________
2	Outage Records	7.5	__________
1	System Type	10.0	__________

Electrical Distribution System
Maintenance & Inspection
Critical Subfactors

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor	Weight no more than 5 Critical Subfactors
5	Periodic Maintenance Plan/Frequency	9.2	__________
4	Training Level	8.0	__________
2	Manning/Experience	9.5	__________
2	Proper Equipment	8.0	__________
1	Substation Maintenance	10.0	__________
1	Line Maintenance	9.0	__________
1	Maintenance History Records	8.0	__________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Diagnostic Tools
Critical Subfactors

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor	Weight no more than 5 Critical Subfactors
6	Coordination Study Plan	8.0	________
3	Supervisory Control and Data Acquisition (SCADA) System	8.7	________
2	Record/As-Built Drawings and Distribution Maps	8.5	________
1	Thermographic Survey	9.0	________
1	Air Force O&M Manuals	10.0	________
1	Manufacturer's Instruction Manuals	9.0	________

Electrical Distribution System
Outage Records
Critical Subfactors

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor	Weight no more than 3 Critical Subfactors
2	Frequency of Outages	9.5	________
1	Cause of Outage (Component Failure vs. Natural Causes)	8.0	________
1	Duration and Extent of Outage Records	9.0	________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Electrical Distribution System
Distribution System Type
Critical Subfactors

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor	Weight no more than 2 Critical Subfactors
1	Underground vs. Overhead Feeders	10.0	________
1	Loadbreak vs. Non-Loadbreak Switching	5.0	________

NOTE: All assigned weighting factors must be integer numbers between 1 and 10. Rating scale is relative (i.e. a "10" is twice as important as a "5") with 10 being the highest.

Appendix C: Transcript of First Round Survey Criteria

CRITICAL COMPONENTS

SUBSTATION:

BREAKERS:

Expert 1 - Inspect breaker mechanism and trip circuits.

EXCELLENT: Low contact resistance and contact travel; Oil dielectric 27 KV or higher; Trip mechanism OK.

FAIR: Oil dielectric between 22 and 27 KV. Everything else OK.

POOR: Oil dielectric less than 22 KV.

Expert 2 - Visual condition, oil test (if oil), check contact and insulation deterioration during internal inspections, check relay condition during calibration.

EXCELLENT: No signs of corrosion, arcing of contacts, or tracking on insulators. Relays pass all calibration requirements (after calibration).

FAIR: Some corrosion stains on paint; minor contact burns and/or insulator contamination.

POOR: Cabinet damaged due to corrosion; Contact pitting and/or visible insulator tracking; Relays damaged so that calibration is impractical.

Expert 3 - Conduct periodic testing.

EXCELLENT: All testing parameters are within specified tolerance.

FAIR: One test parameter outside of specified tolerance.

POOR: More than one test parameter outside of specified tolerance.

Expert 6 - Check interrupting rating (IAC), continuous current rating, age, and spare parts availability.

> **EXCELLENT:** Less than five years old; IAC OK; Current rating OK.
>
> **FAIR:** 10 - 25 years old; Spare parts available; IAC and continuous current rating OK.
>
> **POOR:** More than 25 years old; no spare parts if between 10 and 25 years old; IAC or continuous current rating too low.

Expert 7 - Trip under fault (open/close test cycle). Oil Circuit Breakers (OCB) require more frequent testing than Vacuum Circuit Breakers (VCB).

> **EXCELLENT:** Operates correctly under fault conditions.
>
> **POOR:** Does not operate correctly under fault conditions.

BYPASS SWITCHES:

Expert 2 - Visual inspection and hand test for free operation and good contact wipe.

> **EXCELLENT:** Free operation with clean contact closure.
>
> **FAIR:** Stiff operation but adequate contact alignment for closure.
>
> **POOR:** Requires extreme effort to close.

Expert 8 - Visible inspection. Check for ease of operation and corrosion.

> **EXCELLENT:** No pitting or burn marks; No visible corrosion; Easy to operate.
>
> **POOR:** Visible pits and/or burn marks; Contact surfaces visible corroded.

Expert 5 - Inspect switch contact surfaces where the blades make contact.

> **EXCELLENT:** Pitting is not evident; Arc shorts show little evidence of burning.
>
> **FAIR:** Minor pitting and/or burning evident.
>
> **POOR:** Pitting easily seen; Arc shorts gone.

Expert 3 - Visual inspection.

EXCELLENT: No signs of corrosion or deterioration.

FAIR: Slight corrosion visible at base or seams.

POOR: Badly corroded and deteriorated.

Expert 4 - Visual inspection and test operation of devices.

EXCELLENT: Clean; No corrosion; Operate properly when tested.

POOR: Dirty; Corroded; False operation or failure to operate properly.

PRIMARY TRANSFORMERS (if present):

Expert 6 - Check age and load. Inspect bushings, air seal, oil, and nitrogen air blanket.

EXCELLENT: Less than five years old; Good air seal; Bushings not cracked or leaking; Oil tests good; Loaded less than 100%.

FAIR: Same as above except: 5 - 20 years old; 100 - 115% loaded.

POOR: 25 or more years old; No air seal; Bushings cracked and/or leaking; poor oil tests; Loaded greater than 115%.

Expert 4 - Oil sample and visual inspection (Lab results and incidence of corrosion).

EXCELLENT: New oil; no corrosion.

FAIR: Acceptable oil; Minor corrosion.

POOR: Water in oil/Low dielectric constant; Excessive corrosion and/or leaking case.

Expert 1 - Conduct dielectric test, gas analysis, and sudden pressure relay test.

EXCELLENT: Dielectric tests 27 KV or above; Pressure relay good; Gas analysis performed every six months.

FAIR: Oil dielectric strength 22-27 KV; Pressure relay OK; Gas analysis performed every year,

POOR: Dielectric strength less than 22 KV; Leaking oil; inadequate cooling.

BUSSWORK WITH SUPPORTING INSULATORS:

Expert 2 - Visual inspection of busswork and insulators.

EXCELLENT: No signs of cracked or tracked insulators; No loose hardware.

FAIR: Some minor signs of insulator contamination or tracking.

POOR: Cracked or broken insulators; loose buss connections with associated signs of heating.

Expert 4 - Visual inspection of structure and infra-red scan.

EXCELLENT: Clean; No signs of corrosion; No hot spots indicated in infra-red scan.

POOR: Dirty insulators; Corroded steel and hardware; Infra-red scan shows major hot spots.

LIGHTNING ARRESTORS:

Expert 5 - Inspect substation lightning arrestors for cracks and/or corrosion.

EXCELLENT: No cracks or corrosion apparent.

FAIR: No cracks visible to eye; Small amount of corrosion apparent.

POOR: Cracks easily seen; excessive corrosion.

Expert 6 - Visual inspection along with voltage level and doble tests.

EXCELLENT: No cracks; No tracking marks; Clean; Good doble tests.

FAIR: Apparent cracking; Dirty; Leaking.

POOR: Failed in service.

Expert 2 - Visual Inspection.

EXCELLENT: No visible damage; No visible contamination of porcelain insulators.

FAIR: Contaminated porcelain insulator.

POOR: Obviously damaged or destroyed arrestor.

MAIN SWITCH:

Expert 7 - Shift loads and conduct visual inspection. Check for ease of operation and corrosion.

EXCELLENT: No pitting or burn marks; Easy to operate.

POOR: Excessive corrosion, pitting, or burn marks; Difficult to operate.

Expert 4 - Visual inspection and test operation of devices.

EXCELLENT: Clean; No corrosion; All devices operate properly when tested.

POOR: Dirty; Corroded; False operation or failure to operate properly.

SUBSTATION STRUCTURE:

Expert 2 - Inspect for structural integrity.

EXCELLENT: No signs of corrosion or loose hardware.

FAIR: Minor paint failure with surface rust stains; No loose hardware.

POOR: Major paint failure with structural damage (Rust Pitting); Loose hardware evident.

Expert 10 - Inspect structural integrity of building (assumes enclosed substation).

EXCELLENT: No water leaks; Adequate ventilation/cooling during warm weather; Adequate heating during cold weather.

POOR: Water leaks evident (standing water on floor); Heavy corrosion of equipment due to condensation; Uncomfortably warm, workers unable to work inside longer than five minutes.

RELAYS:

Expert 1 - Relays tested and calibrated by in-house personnel.

EXCELLENT: Set according to short circuit analysis and coordination study using primary current inspection.

FAIR: Set according to short circuit analysis and coordination study using secondary current inspection.

POOR: Tested and reset to original settings without aid of short circuit analysis or coordination study.

FAULT INTERRUPTOR SWITCHES:

Expert 3 - Conduct periodic testing.

EXCELLENT: Switch operates smoothly and successfully.

FAIR: Switch operates with some difficulty.

POOR: Switch is extremely difficult to operate or does not function properly.

PRIMARY DISTRIBUTION CABLE NETWORK: Experts who identified both primary and secondary cable networks listed the same components, inspection criteria, and evaluation criteria for each system. Therefore, this section covers both subsystems.

CONDUCTORS:

Expert 1 - Determine physical characteristics.

EXCELLENT: Concentric neutral or shielded with exterior jacket.

POOR: Not shielded or no concentric neutral; no exterior jacket.

Expert 3 - Visual inspections.

EXCELLENT: No excessive sag or deterioration.

FAIR: Sag appears to exceed limits; Conductors show beginning signs of deterioration.

POOR: Sag is excessive; Conductors appear deteriorated.

Expert 10 - Direct buried cable: Usually stays in good condition unless damaged by external means. Conduct regular hi-pot testing.

> **EXCELLENT:** Regular tests are good; Cable has not been disturbed due to relocation.
>
> **FAIR:** Acceptable insulation resistance.
>
> **POOR:** Considerable number of splices due to cable cuts; Poor insulation resistance; Damaged due to lightning or incorrect fusing (results in overheating under short circuit conditions).

Expert 2 - Visual inspection (Overhead); Hi-Pot test (Underground).

> **EXCELLENT:** No visible corrosion or damage of overhead (OH) lines; Hi-Pot to two times cable voltage rating for underground (UG) cables.
>
> **FAIR:** Visible signs of corrosion, but no failure history for OH; Hi-Pot to 1.5 times cable voltage rating for UG cables.
>
> **POOR:** History of cable failures during storms or high winds for OH lines; Failure history or Hi-Pots show knee of curve at close to cable rating for UG cable.

Expert 4 - Conduct visual and infra-red scans.

> **EXCELLENT:** No visible corrosion; No hot spots.
>
> **FAIR:** Some corrosion; No hot spots.
>
> **POOR:** Infra-red scan reveals hot spots.

Expert 8 - Determine number of fault failures for cable.

> **EXCELLENT:** No fault failures.
>
> **FAIR:** One to three fault failures have occurred.
>
> **POOR:** Cable needs to be replaced if more than three fault failures have occurred.

Expert 6 - Inspect insulation, voltage level, load, and age.

> **EXCELLENT:** Properly loaded; good insulation; used for proper application.
>
> **FAIR:** Cracked insulation; over-loaded.
>
> **POOR:** Failed in service; over 20 years old.

SUPPORTING STRUCTURE (Poles, Conduit, Manholes, etc.):

Expert 4 - Conduct visual inspection of system; take core sample from poles.

EXCELLENT: Clean; no corrosion; No cracks or rot in poles and cross members.

FAIR: Minor corrosion; some cracking of wood members.

POOR: Extensive cracking or rot in wood members/poles; Heavy corrosion on metal.

Expert 2 - Conduct visual inspection and sound poles; Visual inspection of manholes; History of problems (or lack of) during cable installation in conduit. Check insulators.

EXCELLENT: Solid sounding pole with no visible ground level (to 8" underground) rot or damage; Clean manholes (no trash or mud); No record of problems pulling cable; No contamination, visible cracks, or breakage on insulators.

FAIR: Pole has signs of checking or treatment failure but no appreciable damage; Dirty, muddy conduit system, but good history of pulling cables; Surface contamination, but no structural damage of insulators.

POOR: Pole has shell rot (determined by sounding), ground line rot, or insect damage; Collapsed duct system with cable damage; difficult or impossible to pull cable in duct; Cracked or broken insulators.

Expert 3 - Visual inspection of system.

EXCELLENT: Pole assembly shows no visible signs of deterioration or corrosion; Insulators show no signs of damage such as chipping or cracking.

FAIR: Slight signs of deterioration or corrosion can be observed; insulators have small chips or cracks in tangential areas.

POOR: Pole assemble is very deteriorated and/or badly corroded; Insulator is badly damaged, chipped, or cracked.

INSULATION (Type/Characteristics):

E-pert 1 - Inspect for proper voltage class and type.

EXCELLENT: 133% EPR at correct level (15 KV); No faults in past five years.

FAIR: 100% EPR or 100% XLPE; No more than two faults in past five years.

POOR: 100% insulation level of other than EPR or XLPE; Three or more faults in past five years.

NOTE: Most experts included insulation type as a physical characteristic of the conductor itself.

OTHER COMPONENTS (Switches, Sectionalizers, Cutouts, Reclosures, Potheads, etc.):

Expert 7 - Conduct visual inspection for signs of tracking on potheads.

EXCELLENT: No tracking, cracks, or chips.

POOR: Pothead shows extensive tracking.

Expert 6 - Check reclosures and fuses for proper ratings and settings.

EXCELLENT: Good coordination between fuses and reclosures; Fuses protect both transformers and conductors; proper ratings used.

POOR: Failed in service; application exceeds ratings.

Expert 4 - Visual inspection and infra-red scan.

EXCELLENT: No corrosion; No hot spots.

POOR: Excessive corrosion evident on components; Infra-red scan show hot spots at or around components.

Expert 2 - Use visual inspection results and operation history.

EXCELLENT: Good visual condition and no experience with faulty operations.

FAIR: Poor visual condition (corroded or dirty), but no history of faulty operations.

POOR: History of operational failure.

TERMINATIONS (Including Splices):

Expert 8 - Conduct visual inspection of terminations during periodic shutdown; Check splices for proper connection.

EXCELLENT: Splices operating properly; No visible corrosion or loose connections on terminations.

POOR: Splice has failed; Visible corrosion on terminations.

Expert 10 - Conduct visual inspections of terminations for looseness and corrosion.

EXCELLENT: No corrosion and clean after use under near maximum load.

POOR: Visible corrosion, arcing, and cable overheating.

AMPACITY/LOADING:

Expert 1 - Check ampacity of cable.

EXCELLENT: Sufficient ampacity for load growth and emergency backfeeding.

FAIR: Ampacity for load growth; No backfeeding capability.

POOR: No spar capacity.

LIGHTNING ARRESTORS:

No criteria listed (most experts identified lightning protection along with protective devices).

<u>DISTRIBUTION TRANSFORMER NETWORK</u>:

INSULATION MEDIUM:

Expert 2 - Visual inspection and oil test on units over 100 KVA capacity.

EXCELLENT: No visual signs of deterioration; Good results on oil tests.

POOR: Poor results on oil tests.

Expert 1 - Check dielectric strength of larger and/or critical transformers.

EXCELLENT: Dielectric strength 27 KV or greater.

FAIR: Dielectric strength between 22 KV and 27 KV.

POOR: Dielectric strength less than 22 KV.

CASE (Condition):

Expert 6 - Visual inspection of case for leaks. Also check age.

EXCELLENT: Less than 20 years old; no leaks.

FAIR: Between 20 - 25 years old; minor leakage.

POOR: Greater than 25 years old; leaks extensively.

Expert 4 - Check age and conduct visual inspection for deterioration.

EXCELLENT: No leaks; No corrosion; Less than 10 years old.

FAIR: No leaks; Minor corrosion; Between 10 - 15 years old.

POOR: Leaks; Extensive corrosion.

Expert 1 - Visual inspection to see if case is leaking or badly corroded.

EXCELLENT: No rust; No leaks.

FAIR: Minor amount of rust.

POOR: Badly corroded; Leaking.

Expert 2 - Visual inspection of case.

EXCELLENT: No signs of deterioration.

FAIR: Corroded case; Contaminated bushings.

POOR: Badly corroded; Leaks.

TRANSFORMER CHARACTERISTICS:

Expert 6 - Check transformer loading.

EXCELLENT: Transformer not overloaded at any time.

FAIR: Transformer overloaded 1 - 4 hours per day.

POOR: Transformer overloaded 8 - 10 hours per day.

Expert 3 - Check metering and relaying for: oil temperature, fault pressure, and transformer differential.

EXCELLENT: All meter readings are inside specified range.

FAIR: One meter reading is outside the specified range.

POOR: Two or more meter readings are outside specified range.

Expert 9 - Inspect bushings, oil cleanliness, and cooling ability.

EXCELLENT: Oil tests at recommended high voltage rate; Bushings clean with no cracks; Low heat buildup.

FAIR: Moderate heat buildup; Dirty bushings.

POOR: Contaminated oil; Cracked bushings; Heat stress at connections.

PROTECTIVE DEVICES:

Expert 1 - Check for adequate protection of transformer to include: correct fuses, lightning arrestors, and grounding.

EXCELLENT: Transformer is properly fused; Has lightning arrestor and good ground.

FAIR: Inadequate lightning protection but properly fused and has good ground.

POOR: Transformer is not protected.

Expert 6 - Check for correctly sized fuses.

EXCELLENT: Fuses rated for 150% of full load current.

FAIR: Fuses rated for 250% of full load current.

POOR: Fuses rated for 300% or more of full load current.

LIGHTNING ARRESTORS:

No criteria listed (most experts identified lightning protection along with protective devices).

LOAD TAP CHANGERS:

Expert 3 - Check ease of operation.

EXCELLENT: Changer operates smoothly and successfully.

FAIR: Changer operates, but with some difficulty.

POOR: Difficult or impossible to operate changer.

REGULATORS:

Expert 3 - Check voltage meter readings.

EXCELLENT: Voltage reading is within 0.05% of nominal.

FAIR: Voltage reading is within 1.0% of nominal.

POOR: Voltage reading is greater than 1.0% of nominal.

BUSHINGS:

No criteria given.

SWITCHGEAR:

SWITCH:

Expert 8 - Open/Close switch and check for operability and corrosion.

EXCELLENT: Less than 5% of switches on circuit in poor condition.

FAIR: Between 5% and 10% of switches on circuit in poor condition.

POOR: More than 15% of switches on circuit do not operate.

Expert 3 - Check meters and relays for: amps, volts, overcurrent.

EXCELLENT: All readings are within specified tolerance.

FAIR: One reading is outside specified tolerance.

POOR: More than one reading is outside specified tolerance.

Expert 10 - Inspect contacts.

EXCELLENT: Switchgear mechanism moves freely; Contacts are clean; No signs of burning/pitting.

POOR: Contacts are pitted; mechanical movement difficult; Signs of arching; Black smoke film on contact.

CASE:

Expert 3 - Visual inspection for deterioration.

EXCELLENT: No signs of deterioration/corrosion.

FAIR: Slight corrosion at seams, doors, or foundation.

POOR: Badly corroded and deteriorated.

Expert 10 - Visual inspection of case.

EXCELLENT: No signs of corrosion.

POOR: Case is severely corroded.

PROTECTIVE DEVICES:

Coordination Study and Adequate Backfeed Capability Criteria are listed under System Factors Diagnostic Tools and Power Outage Records.

PROPER DEVICES:

Expert 1 - Check to see if proper protective devices are in place to ensure system reliability and safety.

EXCELLENT: All devices coordinate; Devices sectionalize faults to reduce outage effects.

FAIR: Devices at substation only; System not sectionalized to minimize faults.

POOR: Improper devices; Faults not sensed adequately to protect system and public.

CRITICAL SYSTEM SUBFACTORS

MAINTENANCE AND INSPECTION:

PERIODIC MAINTENANCE PLAN / FREQUENCY:

Expert 3 - Review and evaluate maintenance plan.

> **EXCELLENT:** Thorough and complete plan exists and is in use.
>
> **FAIR:** Plan exists, but is very general with no specific detail and breakdown.
>
> **POOR:** No plan exists or existing plan is not used.

Expert 4 - Check plan for completeness and scheduled accomplishment.

> **EXCELLENT:** Plan is complete and scheduled items routinely accomplished.
>
> **POOR:** Plan is incomplete or not scheduled for accomplishment.

TRAINING LEVEL:

Expert 2 - Check training level of shop personnel.

> **EXCELLENT:** All personnel are fully trained; Adequate in-house workload to ensure proficiency levels.
>
> **FAIR:** 75% of personnel fully trained; Adequate in-house workload to ensure proficiency levels of trained personnel and OJT for untrained personnel.
>
> **POOR:** Personnel are not fully trained; Little in-house work accomplished to gain proficiency.

Expert 1 - Check that technicians are allowed sufficient training to attain, and maintain, proficiency.

> **EXCELLENT:** Technicians attend school or seminar every two years.
>
> **FAIR:** Technicians attend school or seminar every three years.
>
> **POOR:** No training program.

MANNING/EXPERIENCE:

Expert 2 - Check authorized manning against available.

EXCELLENT: Sufficient manning to make all required repairs and service calls plus time to accomplish routine maintenance.

FAIR: Not capable of major repair tasking due to insufficient manning.

POOR: Shop is unable to accomplish all routine maintenance.

PROPER EQUIPMENT:

Expert 2 - Check to see if shop equipment is available for system repairs and maintenance.

EXCELLENT: Shop has all necessary tools and equipment; Tools/equipment kept in good repair.

FAIR: Shop has most necessary tools and Equipment; Tools/equipment kept in good repair.

POOR: Shop is poorly equipped; Inadequate maintenance support for major equipment items (bucket and line trucks).

SUBSTATION MAINTENANCE:

Expert 1 - Check level of maintenance in substation for: Transformer, Breakers, and Relays.

EXCELLENT: Maintenance performed yearly.

FAIR: Maintenance performed every other year.

POOR: Performed at intervals of three years, or more; Not performed.

LINE MAINTENANCE:

Expert 1 - Determine extent of physical and visual line checks.

EXCELLENT: Routine pole inspections; Infra-red scans; visual checks with binoculars.

FAIR: Pole checks; Infra-red scans; No real close visual inspection.

POOR: Only spot checks and/or quickie visual inspections performed.

MAINTENANCE HISTORY AND RECORDS:

Expert 3 - Review and evaluate system maintenance records.

EXCELLENT: Thorough and complete maintenance records exist and are routinely updated.

FAIR: Maintenance records exist but are not 100% complete nor always up to date.

POOR: No historical records are maintained.

DIAGNOSTIC TOOLS:

COORDINATION STUDY:

Expert 3 - Review and evaluate system coordination study.

EXCELLENT: Thorough and complete coordination study exists, is implemented, and is operational.

FAIR: Coordination study exists; however, outage records indicate it operates less than 100% coordinated.

POOR: No coordination study exists.

Expert 1 - Evaluate coordination study for: completeness, implementation, ease of modification, and currency.

EXCELLENT: All involved personnel (shops/engineers/management) work together to ensure plan is updated and current; Study is easily and quickly modified when changes occur.

FAIR: All involved personnel (shops/engineers/management) working towards implementation of study; Existing study is difficult, though not impossible, to update.

POOR: Personnel involved (shops/engineers/management) not coordinating efforts to implement study; existing study is impossible to update.

Expert 1 - Check to see if short circuit, load flow, and coordination studies are available.

EXCELLENT: BCE has current studies and base is coordinated in accordance with recommendations.

FAIR: Studies are several years old and have not been updated since minor changes were made.

POOR: Base has no studies which represent current system.

SCADA:

Expert 2 - Determine if system has SCADA or load management system connected.

EXCELLENT: Distribution system is monito[illegible] and operated by a complete SCADA system.

FAIR: System monitoring is provided via a partial SCADA system or is provided as part of the base EMCS system.

POOR: No automatic system monitoring provided.

RECORD/AS-BUILT DRAWINGS and DISTRIBUTION MAPS:

Expert 2 - Determine availability and accuracy of base distribution maps and as-builts.

EXCELLENT: Shop has accurate, updated distribution maps with color coding of feeder circuits and all switch locations marked.

FAIR: Maps are accurate and marked up, but could contain more information.

POOR: Maps are not current.

THERMOGRAPHIC SURVEY:

No criteria given.

AIR FORCE O&M MANUALS:

Expert 4 - Determine if manuals are available for all major equipment items.

EXCELLENT: Shop has manuals.

POOR: Shop does not have necessary manuals.

MANUFACTURER'S INSTRUCTION / OPERATIONS MANUALS:

Expert 4 - Determine if manuals are available for major components.

EXCELLENT: Shop has manuals.

POOR: Shop does not have necessary manuals.

OUTAGE RECORDS:

FREQUENCY; CAUSE; DURATION & EXTENT:

Expert 1 - Check outage records to see if they include: When outage occurred, Where outage occurred, Why outage occurred, Cable or Line type involved, When that part of system was installed, Trip flags (relays), Splice type, etc.

EXCELLENT: Keep all records for 10 years or more to aid in trend analysis of repair/replacement needs.

FAIR: Only outage, cause and trip flag records maintained for 10 years, or, All records maintained for 5 years.

POOR: Only outage event record maintained for 10 years, or, most or all records maintained less than 5 years.

DISTRIBUTION SYSTEM TYPE:

UNDERGROUND vs OVERHEAD FEEDERS:

Expert 2 - Check history of problems with system based on local expertise and environment.

EXCELLENT: Use of a system type that is within the repair capabilities of local labor force and has good endurance under local environmental conditions.

FAIR: Use of a system with good endurance under local environmental conditions, but local labor force not properly equipped to repair or maintain system.

POOR: Use of a system subject to frequent damage or failure under local environmental conditions.

LOAD BREAK vs NON-LOAD BREAK SWITCHING:

Expert 2 - Determine ability to sectionalize system into small portions for maintenance or repair.

EXCELLENT: Each radial can be separated under load from its feeder; major radials can be sectioned off and loop fed from another feeder under load.

FAIR: Each radial can be separated from its feeder; Major radials have load break switches and loop feed capacity.

POOR: System has only non-load break switches, or, switching capability is inadequate.

Appendix D: Summary of Delphi Questionnaire Responses

TABLE 3

SUMMARY OF FIRST ROUND RESPONSES FOR KEY SUBSYSTEMS

# of Experts Selecting Subsystem	Key Subsystem	Average Weight Factor
10	Substation (including main transformers if applicable)	9.4
10	Primary Distribution Cable Network	7.9
8	Distribution Transformer Network	6.9
5	Primary Switchgear	6.8
2	Secondary Distribution Cable Network	6.0
1	Protective Devices	8.0

TABLE 4

SUMMARY OF FIRST ROUND RESPONSES FOR SUBSTATION CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
7	Breakers	8.3
7	Bypass Switches	6.6
4	Primary Transformer (If Present)	9.3
3	Busswork with Supporting Insulators	8.3
3	Lightning Arrestors	5.7
2	Main Switch	10.0
2	Substation Structure	6.5
1	Relays	9.0
1	Fault Interrupter Switches	6.0

TABLE 5

SUMMARY OF FIRST ROUND RESPONSES FOR
PRIMARY DISTRIBUTION CABLE NETWORK
CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
8	Conductors	8.5
7	Supporting Structure (Poles, Conduit, etc.)	7.7
6	Insulation	9.3
6	Other Components (Switches, Cutouts, Sectionalizers, etc.)	6.7
4	Terminations	8.3
2	Ampacity/Loading	8.0
1	Lightning Arrestors	6.0

TABLE 6

SUMMARY OF FIRST ROUND RESPONSES FOR
DISTRIBUTION TRANSFORMER NETWORK
CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
5	Insulation Medium	9.2
5	Case (Condition)	7.6
3	Transformer Characteristics	9.7
3	Protective Devices	9.0
1	Lightning Arrestors	6.0
1	Load Tap Changers	5.0
1	Regulators	8.0
1	Bushings	10.0

TABLE 7

SUMMARY OF FIRST ROUND RESPONSES FOR
SWITCHGEAR CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
4	Switch (Physical Characteristics)	9.3
3	Case (Physical Condition)	5.7
2	Relays	8.0

TABLE 8

SUMMARY OF FIRST ROUND RESPONSES FOR
SECONDARY (LV) DISTRIBUTION CABLE NETWORK
CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
2	Conductors	9.0
1	Supporting Structure (Poles, Conduit, etc.)	8.0
1	Insulation	10.0
1	Other Components (Switches, Cutouts Sectionalizers, Reclosures, etc.)	5.0

TABLE 9

SUMMARY OF FIRST ROUND RESPONSES FOR
PROTECTIVE DEVICES CRITICAL COMPONENTS

# of Experts Selecting Critical Component	Critical Component	Average Weight Factor
1	Coordination Study Implemented	10.0
1	Coordination Study Current	9.0
1	Devices (Type, Characteristics)	9.0
1	Backfeed Capability To Reduce Outage Area	5.0

TABLE 10

SUMMARY OF FIRST ROUND RESPONSES FOR
KEY SYSTEM FACTORS

# of Experts Selecting System Factor	Key System Factor	Average Weight Factor
8	Maintenance and Inspection of System	9.4
7	Diagnostic Tools (SCADA, Maps, Studies)	7.1
2	Outage Records	7.5
1	System Type	10.0

TABLE 11

SUMMARY OF FIRST ROUND RESPONSES FOR
MAINTENANCE AND INSPECTION
CRITICAL SUBFACTORS

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor
5	Periodic Maintenance (Plan/Frequency)	9.2
4	Training Level	8.0
2	Manning/Experience	9.5
2	Proper Equipment	8.0
1	Substation Maintenance	10.0
1	Line Maintenance	9.0
1	Maintenance History (Records)	8.0

TABLE 12

SUMMARY OF FIRST ROUND RESPONSES FOR
DIAGNOSTIC TOOLS CRITICAL SUBFACTORS

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor
6	Coordination Study	8.0
3	SCADA System	8.7
2	Record/As-Built Dwgs Distribution Maps	8.5
1	Thermographic Survey	9.0
1	Air Force O&M Manuals	10.0
1	Manufacturer's Manuals	9.0

TABLE 13

SUMMARY OF FIRST ROUND RESPONSES FOR
OUTAGE RECORDS CRITICAL SUBFACTORS

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor
2	Frequency of Outages	9.5
1	Cause of Outage	8.0
1	Duration and Extent	9.0

TABLE 14

SUMMARY OF FIRST ROUND RESPONSES FOR
SYSTEM TYPE CRITICAL SUBFACTORS

# of Experts Selecting Critical Subfactor	Critical Subfactor	Average Weight Factor
1	Underground/ Overhead	10.0
1	Loadbreak/Non-Loadbreak	5.0

TABLE 15

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
ELECTRICAL DISTRIBUTION SYSTEM
KEY SUBSYSTEMS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Substation	10	10	10	10	10	9	10	10	10	10	10	9.91	YES
Dist Cable Network	8	8	8	7	9	7	10	9	9	9	7	8.27	YES
Dist Transformers			6	8	7	6	8	5	8		7	6.88	YES
Switchgear	8	7	6	9	8	8	8	5	4	8	5	6.91	YES
Sec Cable Network					5	5	7	3	2			4.40	NO
Protective Devices	8	9			6	10	8		7	8		7.00	NO

	Relative (Normalized) Response by Expert ID Number for Subsystems Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Substation	0.38	0.40	0.33	0.29	0.29	0.30	0.28	0.34	0.32	0.37	0.34	0.33
Dist Cable Network	0.31	0.32	0.27	0.21	0.26	0.23	0.28	0.31	0.29	0.33	0.24	0.28
Dist Transformers	0.00	0.00	0.20	0.24	0.21	0.20	0.22	0.17	0.26	0.00	0.24	0.16
Switchgear	0.31	0.28	0.20	0.26	0.24	0.27	0.22	0.17	0.13	0.30	0.17	0.23

TABLE 16

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
SUBSTATION CRITICAL COMPONENTS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Breakers	8	10	8	8	6	7	10	9	8	9	9	8.36	YES
Bypass Switches	8		6	5	5		6	9	5		8	6.50	YES
Primary Transforms	10	10	10	10	10	10			10	7	10	9.67	YES
Busswork	5	9	5	6	0	6	10	6				6.71	NO
Lightning Arrestor	8	9	5			5	7	5	3			6.00	NO
Main Switch				7	7		10	10	4	10		8.00	NO
Substation Structure		9	4									6.50	NO
Relays	8	10		9	9	9	9	8	7	9	7	8.50	YES
Fault Interruptor					8	8				8		8.00	NO

	Relative (Normalized) Response by Expert ID Number for Components Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Breakers	0.24	0.33	0.33	0.25	0.20	0.27	0.40	0.35	0.27	0.36	0.26	0.30
Bypass Switches	0.24	0.00	0.25	0.16	0.17	0.00	0.24	0.35	0.17	0.00	0.24	0.16
Primary Transforms	0.29	0.33	0.42	0.31	0.33	0.38	0.00	0.00	0.33	0.28	0.29	0.27
Relays	0.24	0.33	0.00	0.28	0.30	0.35	0.36	0.31	0.23	0.35	0.21	0.27

TABLE 17

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
DISTRIBUTION CABLE NETWORK CRITICAL COMPONENTS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Conductors	10	10	10	7	8		10	10	10	10	10	9.50	YES
Supporting Structu	8	9	8	6	9	8	10	6	9	9	8	8.18	YES
Insulation	10	10		5		9		8	8	8		8.29	NO
Other Components	8	9	6	10	8	10	8	6	7		6	7.80	YES
Terminations	9		6	9	7	6	10	9	6		8	7.78	YES
Ampacity/Loading		10		8	10	7	9		5			8.17	NO
Lightning Arrestor	5	8			6	5	5	5		6		5.71	NO

	Relative (Normalized) Response by Expert ID Number for Components Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Conductors	0.29	0.36	0.33	0.22	0.25	0	0.26	0.32	0.31	0.53	0.31	0.29
Supporting Structu	0.23	0.32	0.27	0.19	0.28	0.33	0.26	0.19	0.28	0.47	0.25	0.28
Other Components	0.23	0.32	0.2	0.31	0.25	0.42	0.21	0.19	0.22	0	0.19	0.23
Terminations	0.26	0	0.2	0.28	0.22	0.25	0.26	0.29	0.19	0	0.25	0.20

TABLE 18

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
DISTRIBUTION TRANSFORMER NETWORK CRITICAL COMPONENTS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Insulation Medium	10	8	10		7	5	10	7		9	10	8.44	YES
Case	8	8	8		5	10			8	5	6	7.25	YES
Characteristics		9	8	9	6		5	7	10	9	8	7.89	YES
Protective Devices		10	6	10	10	8	10	8	9	8	8	8.70	YES
Lightning Arrestor	9			5	5		8	8	5	7		6.71	NO
Load Tap Changers				6		9	10	5	7			7.40	NO
Regulators				7		7			6			6.67	NO
Bushings	8	8		8		6	10	10		9		8.43	NO

	Relative (Normalized) Response by Expert ID Number for Components Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Insulation Medium	0.56	0.23	0.31	0	0.25	0.22	0.4	0.32	0	0.29	0.31	0.26
Case	0.44	0.23	0.25	0	0.18	0.43	0	0	0.3	0.16	0.19	0.20
Characteristics	0	0.26	0.25	0.47	0.21	0	0.2	0.32	0.37	0.29	0.25	0.24
Protective Devices	0	0.29	0.19	0.53	0.36	0.35	0.4	0.36	0.33	0.26	0.25	0.30

TABLE 19

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
SWITCHGEAR CRITICAL COMPONENTS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Switch	10	10	10	9	10	9	10	10	10	10	10	9.82	YES
Case	8	8	8	8	8	8	7	5	5	5	6	6.91	YES
Relays	9	9	5	10	10	10	5	8	9	7	6	8.00	YES

	Relative (Normalized) Response by Expert ID Number for Components Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Switch	0.37	0.37	0.43	0.33	0.36	0.33	0.45	0.43	0.42	0.45	0.45	0.40
Case	0.3	0.3	0.35	0.3	0.29	0.3	0.32	0.22	0.21	0.23	0.27	0.28
Relays	0.33	0.33	0.22	0.37	0.36	0.37	0.23	0.35	0.38	0.32	0.27	0.32

TABLE 20

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
ELECTRICAL DISTRIBUTION SYSTEM
KEY SYSTEM FACTORS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Maintenance/Insp	10	10	10	10	10	10	9	10	10	10	8	9.73	YES
Diagnostic Tools	8	9	9	9	5	9	10	10	8		10	8.70	YES
Outage Records	5	8	8	8	6	8	8		7	8	5	7.10	YES
System Type								10		7		8.50	NO
	Relative (Normalized) Response by Expert ID Number for System Factors Achieving Consensus												
	1	2	3	4	5	6	7	8	9	10	11	AVG	
Maintenance/Insp	0.43	0.37	0.37	0.37	0.48	0.37	0.33	0.5	0.4	0.56	0.35	0.41	
Diagnostic Tools	0.35	0.33	0.33	0.33	0.24	0.33	0.37	0.5	0.32	0	0.43	0.32	
Outage Records	0.22	0.3	0.3	0.3	0.29	0.3	0.3	0	0.28	0.44	0.22	0.27	

TABLE 21

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
MAINTENANCE AND INSPECTION CRITICAL SUBFACTORS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Maintenance Plan	10	10	10	10	10	10			10	8	10	9.78	YES
Training Level	8	10	9	9	8	9	8	7	9	9	6	8.36	YES
Manning/Experience	9	9	9	6	9	8	10	10	7	9	8	8.55	YES
Proper Equipment	8		8	7		7	10	8	6	8	6	7.56	YES
Substation Maint			8	8	9	6	9	9	8			8.14	NO
Line Maintenance		8			8	5	10					7.75	NO
Maint History Reco	6	8						7		7		7.00	NO
	Relative (Normalized) Response by Expert ID Number for Subfactors Achieving Consensus												
	1	2	3	4	5	6	7	8	9	10	11	AVG	
Maintenance Plan	0.29	0.34	0.28	0.31	0.37	0.29	0	0	0.31	0.24	0.33	0.25	
Training Level	0.23	0.34	0.25	0.28	0.3	0.26	0.29	0.28	0.28	0.26	0.2	0.27	
Manning/Experience	0.26	0.31	0.25	0.19	0.33	0.24	0.36	0.4	0.22	0.26	0.27	0.28	
Proper Equipment	0.23	0	0.22	0.22	0	0.21	0.36	0.32	0.19	0.24	0.2	0.20	

TABLE 22

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
DIAGNOSTIC TOOLS CRITICAL SUBFACTORS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Coordination Study	5	8	10	10	10	7	8	10	10	7	10	8.64	YES
SCADA System	7		9				10	10	6			8.40	NO
Dwgs / Maps	10	10	9	9	9	9	10	7	8	10	6	8.82	YES
Thermographic Sur	8	9	6	6	5	8	8	7	9	9		7.50	YES
Air Force O&M Manuals				8		6				8		7.33	NO
Manufacturer's Inst		8	4	7	7	10	9	5	7	8	5	7.00	YES

	Relative (Normalized) Response by Expert ID Number for Subfactors Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Coordination Study	0.22	0.23	0.34	0.31	0.32	0.21	0.23	0.34	0.29	0.21	0.48	0.29
Dwgs / Maps	0.43	0.29	0.31	0.28	0.29	0.26	0.29	0.24	0.24	0.29	0.29	0.29
Thermographic Sur	0.35	0.26	0.21	0.19	0.16	0.24	0.23	0.24	0.26	0.26	0	0.22
Manufacturer's Ins	0	0.23	0.14	0.22	0.23	0.29	0.26	0.17	0.21	0.24	0.24	0.20

TABLE 23

SECOND ROUND EXPERT RESPONSE SUMMARY FOR
OUTAGE RECORDS CRITICAL SUBFACTORS

	Standard Response by Expert ID Number												
	1	2	3	4	5	6	7	8	9	10	11	AVG	CNS
Frequency	8	9	10	9	8	8	10	9	10	5	10	8.73	YES
Cause	10	10	8	10	10	10	10	10	8	9	5	9.09	YES
Duration/Extent		8	8	8	8	9	10	8	7		6	8.00	YES

	Relative (Normalized) Response by Expert ID Number for Subfactors Achieving Consensus											
	1	2	3	4	5	6	7	8	9	10	11	AVG
Frequency	0.44	0.33	0.38	0.33	0.31	0.3	0.33	0.33	0.4	0.36	0.48	0.36
Cause	0.56	0.37	0.31	0.37	0.38	0.37	0.33	0.37	0.32	0.64	0.24	0.39
Duration/Extent	0	0.3	0.31	0.3	0.31	0.33	0.33	0.3	0.28	0	0.29	0.25

Appendix E: Expert System

```
!  Part 1 of EDS Condition Assessment Analyzer.  Chaining is used to
!  link the various modules of the program.  Chaining is also used to
!  quit program if dBASE files absent.

AUTOQUERY;
EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;

! Actions Block  (Controls sequencing of program)
ACTIONS
     COLOR = 0
     WOPEN 1,2,5,18,69,3       !Set up opening display window
     ACTIVE 1
     DISPLAY " "
     DISPLAY " "
     DISPLAY "                        Welcome to the
                 Electrical Distribution System
                 Condition Assessment Analyzer!"
     DISPLAY " "
     DISPLAY " "
     DISPLAY "                         Developed by:"
     DISPLAY "                       Capt David Paine"
     DISPLAY "                           1 Sep 91"
     DISPLAY " "
     DISPLAY "                          Version 3.0"
     DISPLAY " "
     DISPLAY " "
     DISPLAY "                  (PRESS ANY KEY TO CONTINUE)~"
     CLS
     WCLOSE 1
     DISPLAY ""   ! Thanks to Lt Rick Nelson for shell of this opening
                  ! screen
     DISPLAY " "
     DISPLAY " "
     WOPEN 2,2,2,19,75,3
     ACTIVE 2
     COLOR = 0

     DISPLAY "This Expert System is designed to quantify the condition
of a typical electrical distribution system.  The Condition
Index (CI) numbers provided can then be used as a comparison
between various other electrical distribution systems or
components within a system.  It is intended to be used as an
aid in programming of maintenance and repair projects.  Systems
```

or components with the lowest CI are in the worst shape, and therefore in more need of repair than systems with high a CI.

The expert system should be used by an electrical engineer (preferably the system engineer) who is familiar with all facets of the electrical distribution system. Most of the following questions can be answered only after careful inspection of various portions of the system. It is recommended that the engineer run through the expert system once or twice for familiarization with the questions.

```
(PRESS ANY KEY TO CONTINUE)~"
     CLS
     DISPLAY " "
     DISPLAY "Let's begin our consultation:"
     DISPLAY " "

FIND xformers        ! Check to make sure database(s) is(are) properly
                     ! loaded

     DISPLAY "OK, We're ready to proceed.  Press any key to begin.~"
     WCLOSE 2
     WOPEN 3,1,1,6,77,1      !
     WOPEN 4,8,1,13,36,3     !     OPEN Primary system display windows
     WOPEN 5,8,38,13,39,4    !

!Actions Block for Substation CI Module

     ACTIVE 4
     COLOR = 0
     CLS
     DISPLAY "Executing - Substation module:"
     DISPLAY "
This Module is designed to test
the overall condition of your
primary substation.  Questions
asked are based on average
component condition.  For
explanation of questions,
please type / followed by 3."

     ACTIVE 3
     COLOR = 15
     CLS
     valuesb1 = 34
     FIND SB1         ! Determine the parameters which are used to
     CLS              ! calculate the condition index for substation
     valuesb2 = 33    ! breakers, CI(SCB)
     FIND SB2a
     FIND SB2
```

```
     CLS
     valuesb3 = 33
     FIND SB3
     CLS

     CISCB = (SB1 + SB2 + SB3)        ! Calculate condition index


     valuecisbs = 100
     FIND CISBS       ! Determine the condition index for substation
     CLS              ! bypass switches, CI(SBS)

     FIND primary_xformer    ! Check to see if primary transformer
                             ! is present in substation

WHILETRUE primary_xformer = NO THEN

     CISPT = 100      ! Full value given CI if base does NOT
     CLS              ! Maintain primary substation transformers
RESET primary_xformer         ! End WHILETRUE Loop
END

WHILETRUE primary_xformer = YES THEN

     valuespt = 25
     FIND SPT1        !
     CLS              !
     FIND SPT2        ! Determine the values of the parameters used
     CLS              ! to calculate the condition index for
     FIND SPT3        ! the primary transformer in the substation
     CLS
     FIND SPT4
     CLS

     CISPT = (SPT1 + SPT2 + SPT3 + SPT4)   ! Calculate condition index
RESET primary_xformer                      ! for substation transformer
END                                        ! CI(SPT)

     FIND CISR         ! Determine the value of the condition index for
     CLS               ! substation relays, CI(SR)

! Calculate the Condition Index for Substation, CI(Substation):

CI_Substation = ((0.3*CISCB)+(0.16*CISBS)+(0.27*CISPT)+(0.27*CISR))



     FIND Sub_Rate     ! Determine Rating for Substation

     ACTIVE 5          ! Set up initial display, and record values
     COLOR = 15        ! for CI(Substation) in Summary window
     CLS
```

```
     DISPLAY "                    SUMMARY"
     DISPLAY "MODULE                CI          RATING"
     DISPLAY "Substation          {5CI_Substation}      {9Sub_Rate}"

     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS


! Program chains to and executes from the next module knowledge base
! EDSCOND2.KBS.  This was done due to memory constraints.  All facts
! from this portion are saved and display resumes where we left off.


SAVEFACTS EDSDATA
CHAIN EDSCOND2
;

!Rules block for main module

WHENEVER xformers_NO
IF xformers = NO
THEN                    !Put display in window
     DISPLAY "
The dBASE 3+ file TRANSFOR.DBS must be loaded on the diskette
in drive A:.  Please press any key to quit this consultation.
After both files are loaded onto diskette, you may resume
the consultation from the beginning.~"
CHAIN A:\exit;


!Rules block for substation module

RULE SB1
IF breakers_fair >= 0
     AND breakers_poor >= 0
     AND valuesb1 >= ((2*breakers_fair) + (4*breakers_poor))
THEN SB1 = (34 - ((2*breakers_fair) + (4*breakers_poor)))
ELSE SB1 = 0
BECAUSE "The condition of the substation circuit breakers can be
partially determined by their physical condition.";

RULE SB2a
IF dielectric_fair >= 0
     AND dielectric_poor >= 0
     AND no_operation >= 0
THEN SB2a = (33-((2*dielectric_fair)+(4*(dielectric_poor +
no_operation))))
```

```
BECAUSE "The condition of the substation circuit breakers can be
partially determined by their dielectric strength
(if OCB), and operational results.";

RULE SB2
IF SB2a > 0
THEN SB2 = (SB2a)
ELSE SB2 = 0
BECAUSE "The condition of the substation circuit breakers can be
partially determined by their dielectric strength
(if OCB), and operational results.";

RULE SB3
IF CB_middle_age >= 0
     AND CB_old_age >= 0
     AND valuesb3 >=((2*CB_middle_age) + (4*CB_old_age))
THEN SB3 = (33 - ((2*CB_middle_age) + (4*CB_old_age)))
ELSE SB3 = 0
BECAUSE "The condition of the substation circuit breakers can be
partially determined by their physical condition.";

RULE CISBS
IF switches_fair >= 0
     AND switches_poor >= 0
     AND valuecisbs >= ((6*switches_fair) + (12*switches_poor))
THEN CISBS = (100 - ((6*switches_fair) + (12*switches_poor)))
ELSE CISBS = 0
BECAUSE "The condition of the substation bypass switches can be
determined by their physical condition.";

RULE primary_xformer
IF prim_transformer = Base
THEN primary_xformer = YES
ELSE primary_xformer = NO
BECAUSE "The primary transformer should only be evaluated
when the base is responsible for its maintenance.";

RULE SPT1
IF bushing_condition = YES
THEN SPT1 = 12.5
ELSE SPT1 = 25
BECAUSE "A visual inspection of the physical condition
of the transformer bushings and case is part
of the overall transformer condition.";

RULE SPT2
IF xform_age >= 0
     AND valuespt >= (xform_age*0.4)
THEN SPT2 = (25 - (xform_age*0.4))
ELSE SPT2 = 0
BECAUSE "The age of the transformer contributes
to its overall condition.";
```

```
RULE SPT3_1
IF xformer_load <= 80
THEN SPT3 = 25
BECAUSE "Transformer loading is an indicator of overall condition,
transformers loaded less than 80% capacity rate excellent.";

RULE SPT3_2
IF xformer_load > 80
     AND xformer_load <= 100
THEN SPT3 = 20
BECAUSE "Transformer loading is an indicator of overall condition,
transformers loaded less than 100% capacity rate good.";

RULE SPT3_3
IF xformer_load > 100
     AND xformer_load <= 115
THEN SPT3 = 15
ELSE SPT3 = 10
BECAUSE "Transformer loading is an indicator of overall condition,
transformers loaded less than 115% capacity rate fair.";

RULE SPT4_1
IF type_insul = Oil
     AND trans_dielectric = Greater_than_27KV
THEN SPT4 = 25
BECAUSE "Transformers with oil dielectric strength
greater than 27 KV are in good condition.";

RULE SPT4_2
IF type_insul = Oil
     AND trans_dielectric = Between_22KV_and_27KV
THEN SPT4 = 17.5
BECAUSE "Transformers with oil dielectric strength
between 22 KV and 27 KV are in fair condition.";

RULE SPT4_3
IF type_insul = Oil
     AND trans_dielectric = Less_than_22KV
THEN SPT4 = 12.5
BECAUSE "Transformers with oil dielectric strength
between 22 KV and 27 KV are in fair condition.";

RULE SPT4_4
IF gas_analysis = Six_month_intervals
     AND air_seal = Good_air_seal
     AND type_insul = Gas
     OR type_insul = Other
THEN SPT4 = 25
BECAUSE "Transformers with good air seal and frequent gas analysis
are in good condition.";
```

```
RULE SPT4_5
IF gas_analysis = One_year_intervals
     AND air_seal = Good_air_seal
     AND type_insul = Gas
     OR type_insul = Other
THEN SPT4 = 17.5
ELSE SPT4 = 12.5
BECAUSE "Transformers using other than oil as an insulating medium which
have a
good air seal and frequent gas analysis are in good condition.";

RULE CISR1
IF relay_set = NO
THEN CISR = 50
BECAUSE "The primary factor affecting the condition
of substation relays is whether or not results
of a short circuit analysis/coordination study
are used during setting.";

RULE CISR2
IF relay_set = YES
     AND setting = Primary_Current
THEN CISR = 100
ELSE CISR = 75
BECAUSE "The primary factor affecting the condition
of substation relays is whether or not results
of a short circuit analysis/coordination study
are used during setting.";

RULE Substation_Rating_Excellent
IF CI_Substation >= 90
THEN Sub_Rate = Excellent
BECAUSE "Maximum possible points for CI is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Substation_Rating_Good
IF CI_Substation < 90
AND CI_Substation >= 80
THEN Sub_Rate = Good
BECAUSE "Maximum possible points for CI is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";
```

```
RULE Substation_Rating_Fair_or_Poor
IF CI_Substation < 80
AND CI_Substation >= 60
THEN Sub_Rate = Fair
ELSE Sub_Rate = Poor
BECAUSE "Maximum possible points for CI is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";


!Statements Block for Primary Actions Block.

ASK xformers: "Have maintenance and inspection records for all base
transformers
been input into dBASE 3+ file TRANSFOR.DBS, and has that file been
transferred to the diskette in drive A:?";
CHOICES xformers: YES,NO;

!Statements for Substation Module

ASK breakers_fair: "How many substation circuit breakers show MINOR
signs of
corrosion on cases, or MINOR contact burning, or insulator
contamination? Do not count breakers with excessive wear.";
RANGE breakers_fair:0,25;

ASK breakers_poor: "How many substation circuit breakers show EXTENSIVE
signs of
corrosion on cases, or damaged cases, or MAJOR contact pitting,
or visible insulator tracking?";
RANGE breakers_poor:0,25;

ASK dielectric_fair: "How many oil circuit breakers (OCB) have a
dielectric oil strength test result between 22 KV and 27 KV?";
RANGE dielectric_fair:0,25;

ASK dielectric_poor: "How many oil circuit breakers (OCB) have a
dielectric oil strength test result less than 22 KV?";
RANGE dielectric_poor:0,25;

ASK no_operation:  "When tested under load, how many circuit breakers
failed to operate properly?  Include both oil circuit breakers (OCB) and
vacuum circuit breakers (VCB) in analysis.";
RANGE no_operation:0,25;

ASK CB_middle_age:  "How many substation circuit breakers are between
10 and 25 years old?";
RANGE CB_middle_age:0,25;
```

```
ASK CB_old_age: "How many substation circuit breakers are
more than 25 years old?";
RANGE CB_old_age:0,25;

ASK switches_fair: "How many substation bypass switches demonstrate
stiff operation (but have adequate contact alignment for proper closure)
and have MINOR pitting or burning of contact surfaces?";
RANGE switches_fair:0,20;

ASK switches_poor: "How many substation bypass switches exhibit extreme
effort to close (including those which fail to close), or show excessive
pitting of contact surfaces and severely burned arc shorts?";
RANGE switches_fair:0,20;

ASK prim_transformer: "Who is responsible for maintenance and repair of
the substation primary transformers?";
CHOICES prim_transformer:Base,Local_utility,_,
None_present;

ASK bushing_condition: "Do primary transformers appear to be cracked or
leaking, or is transformer case corroded?";
CHOICES bushing_condition:YES,NO;

ASK xform_age: "What is the age (in years) of the primary transformers
(use average age if more than one transformer is present)?";
RANGE xform_age:0,75;

ASK xformer_load: "What is the normal loading of the primary
transformers compared to rated transformer capacity? State loading as a
percentage -- 85% is entered as 85, 110% is entered as 110.";
RANGE xformer_load:0,200;

ASK type_insul: "What type of insulating medium is used for the
substation primary transformers?";
CHOICES type_insul:Oil,Gas,Other;

ASK trans_dielectric: "What were the results of the oil dielectric
tests for the substation primary transformers?";
CHOICES trans_dielectric:Greater_than_27KV,Between_22KV_and_27KV,
Less_than_22KV;

ASK gas_analysis: "How often is gas analysis performed?";
CHOICES gas_analysis:Six_month_intervals,One_Year_Intervals,
Two_year_intervals,Not_performed;

ASK air_seal: "What is the condition of the transformer air seal?";
CHOICES air_seal:Good_air_seal,Bad_air_seal;
```

```
ASK relay_set:  "Is a current short circuit analysis/coordination study
used as reference to set the substation relays when
performing routine tests and calibration of relays?";
CHOICES relay_set:YES,NO;

ASK setting:  "Are the substation relays set according to the primary
current inspection or the secondary current inspection?";
CHOICES setting:Primary_Current,Secondary_Current;
```

PART 2 OF PROGRAM: FILE EDSCOND2.KBS

```
! Part 2 of EDS Condition Assessment Analyzer. Linked to file
! EDSCOND3.KBS.
AUTOQUERY;
EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;


! Actions Block
ACTIONS
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     COLOR = 15
     LOADFACTS edsdata

     DISPLAY "OK, We're ready to continue.  This program is in several
               parts"
     DISPLAY "due to memory constraints.  Press any key to begin the"
     DISPLAY "second part of this consultation.~"
     WCLOSE 1
     WOPEN 3,1,1,6,77,1
     WOPEN 4,8,1,13,36,3
     WOPEN 5,8,38,13,39,4

     ACTIVE 5
     COLOR = 15
     CLS
     DISPLAY "                    SUMMARY"
     DISPLAY "MODULE                CI            RATING"
     DISPLAY "Substation        {5CI_Substation}       {9Sub_Rate}"


!Actions Block for Power Distribution Module

     ACTIVE 4
     COLOR = 0
     CLS
     DISPLAY "Executing - Distribution module:"
     DISPLAY "
This Module is designed to test
the condition of your power
distribution components, that is
the primary cables and supporting
structures they use. Please type
/ followed by 3 for explanation
of individual questions."
```

```
     ACTIVE 3
     COLOR = 15
     CLS

     valuecnc = 25             !
     FIND CNC1a                !
     CLS                       !  Determine Cable  ondition
     FIND CNC1b                !  for UG and OH cable
     CLS                       !
                               !
     CNC1 = (CNC1a + CNC1b)    !

     valuecnc2 = 50
     FIND CNC2                 ! Determine cable failure history
     CLS

     CIDCNC = (CNC1 + CNC2)    ! Calculate CI for Conductors, CI(DCNC)

     valuecnss = 50            !
     FIND CNSS1                !  Determine parameters for cable
     CLS                       !  supporting structure
     FIND CNSS2                !
     CLS

     CIDCNSS = (CNSS1 + CNSS2)     ! Calculate CI for Supporting
                                   ! Structure

     valuedcnoc = 100
     FIND CIDCNOC              ! Determine CI for Other Components
     CLS

     valuedcnt = 100           !
     FIND CIDCNT               ! Determine CI for Terminations
     CLS                       !

! Calculate the Condition Index for Power Distribution:

CI_Cable = ((0.29*CIDCNC)+(0.28*CIDCNSS)+(0.23*CIDCNOC)+(0.2*CIDCNT))

     FIND Dist_Rate    !Determine Rating for Power Distribution

!Put values in display window.
     ACTIVE 5
     COLOR = 15
     DISPLAY "Distribution     {5CI_Cable}      {9Dist_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS
```

```
! Chain to next module
SAVEFACTS EDSDATA2
CHAIN EDSCOND3
;

!Rules Block for Power Distribution Condition Module


RULE CNC1a
IF hipot15 >= 0
     AND hipot10 >= 0
     AND valuecnc >= ((hipot15) + (2*hipot10))
THEN CNC1a = (25 - ((hipot15) + (2*hipot10)))
ELSE CNC1a = 0
BECAUSE "The Hi Pot test results are a good indicator of overall
         conductor condition for underground high-voltage cables.";

RULE CNC1b
IF OH_lines_fair >= 0
     AND OH_lines_poor >= 0
     AND valuecnc >= ((OH_lines_fair) + (2*OH_lines_poor))
THEN CNC1b = (25 - ((OH_lines_fair) + (2*OH_lines_poor)))
ELSE CNC1b = 0
BECAUSE "Visible inspection of overhead high-voltage lines is a good
         indicator of overall conductor condition for the overhead cable
         network.";

RULE CNC2
IF failures_low >= 0
     AND failures_high >= 0
     AND valuecnc2 >= ((2*failures_low) + (4*failures_high))
THEN CNC2 = (50 - ((2*failures_low) + (4*failures_high)))
ELSE CNC2 = 0
BECAUSE "The history of fault failures for a cable (both overhead and
         underground) is a good indicator of conductor condition.";

RULE CNSS1
IF poles_fair >= 0
     AND poles_poor >= 0
     AND valuecnss >= ((0.5*poles_fair) + (poles_poor))
THEN CNSS1 = (50 - ((0.5*poles_fair) + (poles_poor)))
ELSE CNSS1 = 0
BECAUSE "Visible inspection results of the overhead distribution poles
is a good indicator of the condition of the supporting structure.";

RULE CNSS2
IF manholes_fair >= 0
     AND manholes_poor >= 0
     AND valuecnss >= ((0.5*manholes_fair) + (manholes_poor))
THEN CNSS2 = (50 - ((0.5*manholes_fair) + (manholes_poor)))
ELSE CNSS2 = 0
```

```
BECAUSE "Visible inspection results of the overhead distribution poles
is a good indicator of the condition of the supporting structure.";

RULE CIDCNOC
IF components_fair >= 0
     AND components_poor >= 0
     AND valuedcnoc >= ((components_fair) + (2*components_poor))
THEN CIDCNOC = (100 - ((components_fair) + (2*components_poor)))
ELSE CIDCNOC = 0
BECAUSE "Visual or infra-red inspection of other components (switches,
sectionalizers, cutouts, reclosures, potheads, etc.) is a good
indicator of cable network condition.";

RULE CIDCNT
IF poor_terminations >= 0
     AND valuedcnt >= (3*poor_terminations)
THEN CIDCNT = (100 - (3*poor_terminations))
ELSE CIDCNT = 0
BECAUSE "The number of poor high-voltage cable terminations, determined
by
visual inspection or infra-red scan, is a factor in distribution
cable network condition.";

RULE Distribution_Rating_Excellent
IF CI_Cable >= 90
THEN Dist_Rate = Excellent
BECAUSE "Maximum possible points for CI_Cable is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Distribution_Rating_Good
IF CI_Cable < 90
     AND CI_Cable >= 80
THEN Dist_Rate = Good
BECAUSE "Maximum possible points for CI_Cable is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Distribution_Rating_Fair_or_Poor
IF CI_Cable < 80
     AND CI_Cable >= 60
THEN Dist_Rate = Fair
ELSE Dist_Rate = Poor
```

```
BECAUSE "Maximum possible points for CI_Cable is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  79.99 ==> Fair
       0  - 59.99 ==> Poor";


!Statements Block for Power Distribution Module


ASK hipot15:  "How many high-voltage underground distribution cables
tested to approximately 1.5 times cable rating during Hi Pot tests?
Count cables with test results between 1.2 times and 1.75 times cable
rating.";
RANGE hipot15:0,25;

ASK hipot10:  "How many high-voltage underground distribution cables
tested to less than 1.2 times cable rating during Hi Pot tests.?";
RANGE hipot10:0,25;

ASK OH_lines_fair:  "How many of the overhead high-voltage distribution
conductors would you rate fair?  Fair condition is indicated by MINOR
corrosion and/or line sag which appears to exceed recommended limits,
but is not excessive.";
RANGE OH_lines_fair:0,75;

ASK OH_lines_poor:  "How many of the overhead high-voltage distribution
conductors would you rate poor?  Poor condition is indicated by extreme
corrosion and/or line sag which appears to be excessive.";
RANGE OH_lines_fair:0,50;

ASK failures_low:  "How many high-voltage conductors, both overhead and
underground, have experienced between 1 and 3 fault failures
without being replaced?";
RANGE failures_low:0,25;

ASK failures_high:  "How many high-voltage conductors, both overhead and
underground, have experienced more than 3 fault failures
without being replaced?";
RANGE failures_low:0,25;

ASK poles_fair:  "How many of the poles supporting high-voltage
conductors would you rate fair?  Fair condition is indicated by signs of
checking or treatment failure on poles, or by surface contamination of
support insulators (no structural damage to insulator).";
RANGE poles_fair:0,100;

ASK poles_poor:  "How many of the poles supporting high-voltage
conductors would you rate poor?  Poor condition is indicated by shell
rot (determined by sounding poles), and/or by cracked or broken
(structurally failed) support insulators.";
```

```
RANGE poles_poor:0,100;

ASK manholes_fair:  "How many of the manholes and/or conduit runs
supporting high-voltage conductors would you rate fair?  Fair condition
is indicated by manholes or conduit sections which appear muddy, but
which have a good history of pulling cables.";
RANGE manholes_fair:0,100;

ASK manholes_poor:  "How many of the manholes and/or conduit runs
supporting high-voltage conductors would you rate poor?  Poor condition
is indicated by collapsed conduit sections and/or history of cable
pulling difficulty.";
RANGE manholes_poor:0,100;

ASK components_fair:  "How many other distribution cable network
components (switches, sectionalizers, cutouts, reclosures, potheads,
etc.) would you rate fair?  Fair condition is indicated if components
show minor corrosion but have no history of faulty operations.
Components do not show hot on infra-red scan.";
Range components_fair:0,100;

ASK components_poor:  "How many other distribution cable network
components (switches, sectionalizers, cutouts, reclosures, potheads,
etc.) would you rate poor?  Poor condition is indicated when components
show major corrosion, have a history of faulty operations, or show as a
hot-spot on infra-red scans.";
Range components_poor:0,100;

ASK poor_terminations:  "How many of the high-voltage cable terminations
would you rate as poor.  Poor condition is indicated by corrosion and/or
looseness of connection.  Poor connections will show as hot-spots on
infra-red scan.";
RANGE poor_terminations:0,50;
```

PART 3 OF PROGRAM: FILE EDSCOND3.KBS

```
! Part 3 of EDS Condition Assessment Analyzer. Linked to file
! EDSCOND4.KBS.
! Contains Distribution Transformer Network Module
! and Switchgear Module

AUTOQUERY;
EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;


! Actions Block

ACTIONS
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     COLOR = 15
     LOADFACTS edsdata2

DISPLAY "OK, We're ready to continue. This program is in several parts"
     DISPLAY "due to memory constraints. Press any key to begin the"
     DISPLAY "third part of this consultation, execution of Distribution
               Transformer Network Module and Switchgear Module.~"
     WCLOSE 1

     WOPEN 3,1,1,6,77,1
     WOPEN 4,8,1,13,36,3
     WOPEN 5,8,38,13,39,4

     ACTIVE 5
     COLOR = 15
     CLS
     DISPLAY "                   SUMMARY"
     DISPLAY "MODULE              CI            RATING"
     DISPLAY "Substation         {5CI_Substation}       {9Sub_Rate}"
     DISPLAY "Cable Network      {5CI_Cable}       {9Dist_Rate}"

!Actions Block for Distribution Transformer Module

     ACTIVE 4
     COLOR = 0
CLS

DISPLAY "EXECUTING Transformer Module:

This module will access info
in your transformer database.
Ratings you have given each
```

```
transformer during routine
maintenance and inspections
will be used to calculate the
overall rating."

ACTIVE 3
DISPLAY " All data for this module comes from the transformer database
          file,  TRANSFOR.DBF, on the diskette in drive A:."


         Exc = 0                        !
         Good = 0                          !
         Fair = 0                            ! Initialize count variables
         Poor = 0                          !
        Total = 0                        !
     Exc_Cond = Excellent                !
    Good_Cond = Good                     ! Set conditional variables for
    Fair_Cond = Fair                     ! Whileknown clauses
    Poor_Cond = Poor                     !

WHILEKNOWN Condition         ! Determine Total Number of Records
     RESET Condition
     GET ALL,A:\transfor,CONDITION
     Total = ((Total)+1)
END
CLOSE A:\transfor
     Total = ((Total) - 1) ! Adjust for extra cycle through WHILEKNOWN
CLAUSE

WHILEKNOWN Condition      ! Determine total number of records rated
                          ! Excellent
     RESET Condition
     GET Exc_Cond=Condition,A:\transfor,CONDITION
     Exc = ((Exc)+1)
END
     Exc = ((Exc)-1)      ! Adjust for extra cycle through WHILEKNOWN
CLAUSE
CLOSE A:\transfor

WHILEKNOWN Condition      ! Determine total number of records rated Good
     RESET Condition
     GET Good_Cond=Condition,A:\transfor,CONDITION
     Good = ((Good)+1)
END
     Good = ((Good)-1)    ! Adjust for extra cycle through WHILEKNOWN
CLAUSE
CLOSE A:\transfor
```

```
WHILEKNOWN Condition      ! Determine total number of records rated Fair
     RESET Condition
     GET Fair_Cond=Condition,A:\transfor,CONDITION
     Fair = ((Fair)+1)
END
     Fair = ((Fair)-1)    ! Adjust for extra cycle through WHILEKNOWN
CLAUSE
CLOSE A:\transfor

WHILEKNOWN Condition      ! Determine total number of records rated Poor
     RESET Condition
     GET Poor_Cond=Condition,A:\transfor,CONDITION
     Poor = ((Poor)+1)
END
     Poor = ((Poor)-1)    ! Adjust for extra cycle through WHILEKNOWN
CLAUSE
CLOSE A:\transfor

!Calculate Condition Index for Power Transformation Module

CI_Transformers =
((((Poor)*40)+((Fair)*70)+((Good)*85)+((Exc)*100))/(Total))

     FIND Pwr_Trans_Rate   ! Determine rating for Transformer Network
                           ! Module

     ACTIVE 5
     COLOR = 15
    DISPLAY "Transformers     {5CI_Transformers}      {9Pwr_Trans_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS

!  Actions Block for Switchgear Module

ACTIVE 4       !Change windows
COLOR = 0
CLS
DISPLAY "EXECUTING - Switchgear Module:

This module is designed to assess
the overall condition of the
switchgear components in the
electrical distribution system.
Only quantities of components rated
fair or poor are required, along
with total quantity inspected.
For an explanation of each
question, type / followed by 3."
```

```
ACTIVE 3        !Change windows
COLOR = 15
CLS

     valueciss = 100
     FIND CISS             ! Determine the condition index for
                           ! Switchgear Switches, CI(SS)


WHILETRUE  switches_total < (poor_switc) THEN
     CLS
     DISPLAY "The number of switches rated poor cannot exceed the total
number of switches evaluated.  Please make sure the correct quantities
are input for each variable.  Press any key to continue.~"
     CLS
     RESET poor_switc          !  Check to make sure variables are
     RESET switches_total      !  input correctly.  Reset if not.
     RESET CISS
     FIND CISS
END

     valuecisc = 100
     FIND CISC             ! Determine the condition index for
                            ! Switchgear Cases, CI(SC)

WHILETRUE  cases < ((cas_poor)+(cas_fair)) THEN
     CLS
     DISPLAY "The number of cases rated poor or fair cannot exceed the
total number of cases evaluated.  Please make sure the correct
quantities are input for each variable.  Press any key to continue.~"
     CLS
     RESET cas_poor        !  Check to make sure variables are input
     RESET cas_fair
     RESET cases       !  correctly.  Reset if not.
     RESET CISC
     FIND CISC
END

WHILETRUE CISC < 0 THEN      ! Adjust the CI to 0 if less than 0
     CISC = 0
END

     FIND CISSR            ! Determine the condition index for
                           ! Switchgear Relays, CI(SSR)


!  Calculate the condition index for Switchgear, CI(Switchgear)
     CI_Switchgear = ((0.40*CISS) + (0.28*CISC) + (0.32*CISSR))
```

```
     FIND Switchgear_Rate   !Determine rating for Switchgear Module

     ACTIVE 5
     COLOR = 15
     DISPLAY "Switchgear       {5CI_Switchgear}      {9Switchgear_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS


! Remainder of program chains to and executes from the knowledge base
! EDSCOND4.KBS.  This was done due to memory constraints.  All facts
! from this portion are saved and display resumes where we left off.

SAVEFACTS EDSDATA3
CHAIN EDSCOND4;

!Rules Block for Distribution Transformer Network Module

RULE Pwr_Trans_Rating_Excellent
IF CI_Transformers >= 90
THEN Pwr_Trans_Rate = Excellent
BECAUSE "Maximum possible points for CI_Transformers is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Pwr_Trans_Rating_Good
IF  CI_Transformers < 90
     AND CI_Transformers >= 80
THEN Pwr_Trans_Rate = Good
BECAUSE "Maximum possible points for CI_Transformers is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Pwr_Trans_Rating_Fair_or_Poor
IF CI_Transformers < 80
AND CI_Transformers >= 60
THEN Pwr_Trans_Rate = Fair
ELSE Pwr_Trans_Rate = Poor
```

```
BECAUSE "Maximum possible points for CI_Transformers is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";


! Rules Block for Switchgear Module

RULE CISS
IF switches_total >= 0
     AND poor_switc >= 0
     AND valueciss >= ((200*poor_switc)/(switches_total))
THEN CISS = (100 - ((200*poor_switc)/(switches_total)))
ELSE CISS = 0
BECAUSE "The percentage of switches rated poor can be used to
determine the condition index of the switchgear switches.";

RULE CISC
IF cases >= 0
     AND cas_fair >=0
     AND cas_poor >= 0
!     AND valuecisc >= (100*((cas_fair)/(cases) + (2*cas_poor)/(cases)))
THEN CISC = (100*(1 - (((cas_fair)/(cases) + (2*cas_poor)/(cases)))))
ELSE CISC = 0
BECAUSE "The percentage of cases rated fair or poor can be used to
determine the condition index of the switchgear cases.";

RULE CISSR1
IF switch_relay_set = NO
THEN CISSR = 50
BECAUSE " The primary factor affecting the condition of switchgear
relays is whether or not results of a short circuit analysis/
coordination study are used during setting.";

RULE CISSR2
IF switch_relay_set = YES
     AND relay_setting = Primary_Current
THEN CISSR = 100
ELSE CISSR = 75
BECAUSE "Use of Primary Current settings during relay calibration
result in a more coordinated system than do Secondary
Current settings.";

RULE Switchgear_Rating_Excellent
IF CI_Switchgear >= 90
THEN Switchgear_Rate = Excellent
```

```
BECAUSE "Maximum possible points for CI_Switchgear is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Switchgear_Rating_Good
IF  CI_Switchgear < 90
     AND CI_Switchgear >= 80
THEN Switchgear_Rate = Good
BECAUSE "Maximum possible points for CI_Switchgear is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Switchgear_Rating_Fair_or_Poor
IF CI_Switchgear < 80
AND CI_Switchgear >= 60
THEN Switchgear_Rate = Fair
ELSE Switchgear_Rate = Poor
BECAUSE "Maximum possible points for CI_Switchgear is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";


! Statements Block for Switchgear Module

ASK switches_total: "How many of the base's switchgear switches were
examined for this analysis?  The total number of switches examined will
be used to determine the percentage of switches rated poor.";
RANGE switches_total:0,250;

ASK poor_switc: "How many of the examined switchgear switches received
a rating of poor?  Poor condition is indicated by extreme difficulty
in operation (include inoperable switches), or by contacts which are
excessively corroded, burned, or pitted.";
RANGE poor_switc:0,250;

ASK cases: "How many of the base's switchgear cases were examined for
this analysis?  The total number of cases examined will be
used to determine the percentages of cases rated fair or poor.";
RANGE switches_total:0,250;
```

```
ASK cas_fair: "How many of the examined switchgear cases received a
rating of fair? Fair condition is indicated by minor signs of
deterioration or corrosion (i.e. cases which have visible rust
but are not rusted through the metal).";
RANGE cas_poor:0,250;

ASK cas_poor: "How many of the examined switchgear cases received a
rating of poor? Poor condition is indicated by excessive deterioration
or corrosion (i.e. cases which have areas rusted through the metal).";
RANGE cas_poor:0,250;

ASK switch_relay_set: "Are the results of a up-to-date short circuit
analysis/coordination study used to set the switchgear relays during
routine testing and calibration?";
CHOICES switch_relay_set:YES,NO;

ASK relay_setting: "Are the relays calibrated and set using the Primary
Current inspection results, or the Secondary Current inspection
results of the Coordination Study?";
CHOICES relay_setting:Primary_Current,Secondary_Current;
```

PART 4 OF PROGRAM: FILE EDSCOND4.KBS

```
! Part 4 of EDS Condition Assessment Analyzer. Linked to file
! EDSCOND5.KBS.
! Contains Maintenance/Inspection, and Diagnostic Tools Modules

AUTOQUERY;
EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;


! Actions Block

ACTIONS
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     COLOR = 15
     LOADFACTS edsdata3

     DISPLAY "OK, We're ready to continue.  This program is in several
             parts"
     DISPLAY "due to memory constraints.  Press any key to begin the"
     DISPLAY "fourth part of this consultation, execution of
             Maintenance/"
     DISPLAY "Inspection, and Diagnostic Tools Modules.~"
     WCLOSE 1
     WOPEN 3,1,1,6,77,1
     WOPEN 4,8,1,13,36,3
     WOPEN 5,8,38,13,39,4

     ACTIVE 5
     COLOR = 15
     CLS
     DISPLAY "                    SUMMARY"
     DISPLAY "MODULE               CI             RATING"
     DISPLAY "Substation          {5CI_Substation}       {9Sub_Rate}"
     DISPLAY "Cable Network       {5CI_Cable}       {9Dist_Rate}"
     DISPLAY "Transformers       {5CI_Transformers}       {9Pwr_Trans_Rate}"
     DISPLAY "Switchgear          {5CI_Switchgear}       {9Switchgear_Rate}"

!Actions Block for Maintenance and Inspection Module

     ACTIVE 4        !Change windows
     COLOR = 0
     CLS
     DISPLAY "EXECUTING - Miant/Insp Module:
```

```
This module is designed to
assess the overall condition
of the maintenance and
inspection program for the
electrical distribution system.
For an explanation of each
question, type / followed by 3."

     ACTIVE 3          !Change windows
     COLOR = 15
     CLS

     FIND CIMIMP            ! Determine the condition index for
                            ! maintenance plans

     FIND CIMITL            ! Determine condition index for
                            ! training level

     FIND CIMIME            ! Determine condition index for
                            ! manning/experience

     FIND CIMIPE            ! Determine condition index for
                            ! proper equipment

! Calculate the condition index for Maintenance and Inspection,
! CI(Maint)

     CI_Maint =
((0.25*CIMIMP)+(0.27*CIMITL)+(0.28*CIMIME)+(0.20*CIMIPE))

     FIND Maint_Rate

     ACTIVE 5
     COLOR = 15
     DISPLAY "Maintenance      {5CI_Maint}      {9Maint_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue..."
     CLS

!  Actions Block for Diagnostic Tools Module

ACTIVE 4        !Change windows
COLOR = 0
CLS
DISPLAY "EXECUTING - Diagnostics Module:


This module is designed to assess
the overall condition of the
diagnostic tools available to
```

```
aid in the evaluation and
maintenance of the electrical
distribution system.
For an explanation of each
question, type / followed by 3."

     ACTIVE 3        !Change windows
     COLOR = 15
     CLS

     FIND CIDTCS           ! Determine the condition index for
                           ! coordination study

     FIND DM1              ! Determine parameters for drawings/maps
     FIND DM2              ! critical system subfactor

     CIDTDM = (DM1 +DM2)   ! Calculate the condition index for
                           ! drawings/maps

     FIND CIDTTS           ! Determine the condition index for
                           ! thermographic surveys

     FIND CIDTMI           ! Determine the condition index for
                           ! manufacturers' instruction manuals

     CI_Tools = ((0.29*CIDTCS)+(0.29*CIDTDM)
                           +(0.22*CIDTTS)+(0.20*CIDTMI))

     FIND Diag_Tools_Rate

     ACTIVE 5
     COLOR = 15
     DISPLAY "Diagnostic Tools {5CI_Tools}      {9Diag_Tools_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS

! Remainder of program chains to and executes from the knowledge base
! EDSCOND5.KBS.  This was done due to memory constraints.  All facts
! from this portion are saved and display resumes where we left off.

SAVEFACTS EDSDATA4
CHAIN EDSCOND5
;
```

```
!Rules Block for Maintenance and Inspection Module

RULE CIMIMP1
IF plan = YES
     AND update = Often
     AND coverage = Thorough
THEN CIMIMP = 100
BECAUSE "A maintenance plan must be thorough, up-to-date, and used
regularly to be effective.";

RULE CIMIMP2
IF plan = YES
     AND update = Seldom
     OR coverage = General
THEN CIMIMP = 70
ELSE CIMIMP = 40
BECAUSE "A maintenance plan must be thorough, up-to-date, and used
regularly to be effective.";

RULE CIMITL1
IF trained = YES
     AND work = YES
     AND tech_train = Two_Years
THEN CIMITL = 100
BECAUSE "Technicians must be trained, and proficiency levels maintained
to ensure adequate maintenance can be performed.";

RULE CIMITL2
IF trained = YES
     AND work = NO
     OR tech_train = Three_Years
THEN CIMITL = 70
BECAUSE "Technicians must be trained, and proficiency levels maintained
to ensure adequate maintenance can be performed.";

RULE CIMITL3
IF trained = NO
     AND work = YES
     OR tech_train = Two_Years
THEN CIMITL = 70
ELSE CIMITL = 40
BECAUSE "Technicians must be trained, and proficiency levels maintained
to ensure adequate maintenance can be performed.",

RULE CIMIME1
IF manning = YES
THEN CIMIME = 100
BECAUSE "If exterior electric shop is unable to perform routine repairs
and maintenance on the electrical distribution system, system
condition may be degraded.";
```

```
RULE CIMIME2
IF no_manpower = YES
THEN CIMIME = 40
ELSE CIMIME = 70
BECAUSE "If exterior electric shop is unable to perform routine repairs
and maintenance on the electrical distribution system, system
condition may be degraded.";

RULE CIMIPE1
IF equipped = All
     AND equip_maint = Good
THEN CIMIPE = 100
BECAUSE "The shop must be properly equipped, and equipment/tools
properly maintained, to ensure system is maintained
in good condition.";

RULE CIMIPE2
IF equipped = Most
     AND equip_maint = Good
THEN CIMIPE = 70
ELSE CIMIPE = 40
BECAUSE "The shop must be properly equipped, and equipment/tools
properly maintained, to ensure system is maintained
in good condition.";

RULE Maint_Rating_Excellent
IF CI_Maint >= 90
THEN Maint_Rate = Excellent
BECAUSE "Maximum possible points for CI_Maint is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Maintenance_Rating_Good
IF  CI_Maint < 90
     AND CI_Maint >= 80
THEN Maint_Rate = Good
BECAUSE "Maximum possible points for CI_Maint is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Maintenance_Rating_Fair_or_Poor
IF CI_Maint < 80
AND CI_Maint >= 60
THEN Maint_Rate = Fair
ELSE Maint_Rate = Poor
```

```
BECAUSE "Maximum possible points for CI_Maint is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";


! Rules Block for Diagnostic Tools Module

RULE CIDTCS1
IF coord_study = YES
     AND coordinated = YES
THEN CIDTCS = 100
BECAUSE "A properly coordinated electrical distribution system is
essential to maintaining the system in good condition.";

RULE CIDTCS1
IF old_study = YES
     AND coordinated = YES
THEN CIDTCS = 70
ELSE CIDTCS = 40
BECAUSE "A properly coordinated electrical distribution system is
essential to maintaining the system in good condition.";

RULE DM1-1
IF maps_comp = YES
     AND maps_cur = YES
THEN DM1 = 50
BECAUSE "Distribution maps must be comprehensive and current to
be effective";

RULE DM1-2
IF maps_comp = NO
     AND maps_cur = YES
THEN DM1 = 35
ELSE DM1 =20
BECAUSE "Distribution maps must be comprehensive and current to
be effective";

RULE DM2-1
IF draw = YES
     AND draw_update = Six_Months
THEN DM2 = 50

BECAUSE "Record Drawings and As-Builts should be accurate and should
be updated in a timely manner.";

RULE DM2-2
IF draw = YES
     AND draw_update = One_Year
THEN DM2 = 35
```

```
ELSE DM2 = 20
BECAUSE "Record Drawings and As-Builts should be accurate and should
be updated in a timely manner.";

RULE CIDTTS
IF survey_avail = YES
THEN CIDTTS = 100
ELSE CIDTTS = 50
BECAUSE "Thermographic surveys of the electrical distribution system car
aid in the diagnosis of system problems.";

RULE CIDTMI
IF manuals_avail = YES
THEN CIDTMI = 100
ELSE CIDTMI = 50
BECAUSE "Manufacturers' Instruction Manuals are necessary to properly
maintain critical system components.";

RULE Diagnostic_Rating_Excellent
IF CI_Tools >= 90
THEN Diag_Tools_Rate = Excellent
BECAUSE "Maximum possible points for CI_Tools is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Diagnostics_Rating_Good
IF  CI_Tools < 90
     AND CI_Tools >= 80
THEN Diag_Tools_Rate = Good
BECAUSE "Maximum possible points for CI_Tools is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Diagnostics_Rating_Fair_or_Poor
IF CI_Tools < 80
AND CI_Tools >= 60
THEN Diag_Tools_Rate = Fair
ELSE Diag_Tools_Rate = Poor
BECAUSE "Maximum possible points for CI_Tools is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";
```

```
! Statements Block for Maintenance and Inspection Module


ASK plan: "Is there a written plan for performance of routine
maintenance and repair of the electrical distribution system, and is
that plan in regular use?  If a plan exists but is NOT followed,
answer NO to this question.";

CHOICES plan:YES,NO;

ASK update: "How often is the existing maintenance plan updated?  Often
would include updates on an 'as needed' basis for major system
changes.  Seldom would signify fixed update intervals of between
two and three years, regardless of major system changes.";

CHOICES update:Often,Seldom,Never;

ASK coverage: "How thorough is the maintenance plan coverage?  Thorough
coverage includes distribution system critical components (i.e.
Transformers, Reclosures, Switchgear, Breakers, Primary Conductors,
etc.).  General coverage includes major systems but does not break out
specific items.";

CHOICES coverage:Thorough, General,Inadequate;

ASK trained: "Are all exterior electric shop personnel fully trained and
qualified for their job.  Answer YES if more than 80% of the shop
personnel are trained and maintain required proficiency levels.
";

CHOICES trained:YES,NO;

ASK work: "Is sufficient in-house work accomplished to allow all
shop personnel to maintain proficiency and to allow sufficient
on-the-job training (OJT) for untrained personnel?
";

CHOICES work:YES,NO;

ASK tech_train: "What is the interval between scheduled technical
training for shop personnel?  Training should include seminars and
workshops dealing with electrical distribution systems and components.";

CHOICES tech_train:Two_Years,Three_Years,No_Program;

ASK manning: "Does the exterior electric shop currently have adequate,
experienced manning to accomplish ALL required repairs, service
calls, and routine maintenance?";

CHOICES manning:YES,NO;
```

```
ASK no_manpower: "Is the exterior electric shop unable to accomplish
routine maintenance and repair due to lack of sufficient
manpower or lack of experienced personnel?";
CHOICES no_manpower:YES,NO;

ASK equipped: "How well equipped is the exterior electric shop?  Answer
should consider whether or not shop has all tools and equipment
necessary to perform routine maintenance and repair jobs.";
CHOICES equipped:All, Most,Insufficient_Tools,Insufficient_Equipment;

ASK equip_maint: "What is the level of maintenance of existing tools and
equipment (i.e. are tools and equipment items kept is a good
state of repair)?";
CHOICES equip_maint:Good,Poor;


! Statements Block for Diagnostic Tools Module

CHOICES coord_study,coordinated,old_study,maps_comp,maps_cur,draw,
     draw_update,survey_avail,manuals_avail:YES,NO;

ASK coord_study:  "Is a current, updated short circuit
analysis/coordination study available for use in coordinating the
electrical distribution system?  Answer NO if study is several years old
and has not been kept current.";

ASK old_study:  "Is there an older short circuit analysis/coordination
study available which could be updated to reflect current system status
for the electrical distribution system?";

ASK coordinated:  "Has the base electrical distribution system been
coordinated according to the recommendations of the existing short
circuit analysis/coordination study?  Answer YES regardless of the
currency of study.";

ASK maps_comp:  "Are the exterior electric shop's distribution maps
complete, accurate, and up-to-date?  Answer yes if maps are color coded,
feeder circuits are clearly marked, and switch locations are clearly
marked.  All necessary information should be on maps.";

ASK maps_cur:   "Are the distribution system maps current?  Answer YES
if maps are updated on a regular basis to reflect changes in system even
if all necessary information is not contained on maps.";

ASK draw:  "Are all record and as-built drawings accurate?  Drawings
should reflect current system configuration and be updated on a regular
basis. ";

ASK draw_update:  "How long does it usually take for record and as-built
drawings to be updated after any changes occur?";
CHOICES draw_update:Six_Months,One_Year,1.5_Years_or_More;
```

```
ASK survey_avail: "Do you have an accurate, current thermographic
survey (infra-red scan) of the base electrical distribution system?
Thermographic survey should include all major critical components.";

ASK manuals_avail: "Are the manufacturers' instruction manuals
available for all major electrical distribution system components?";
```

PART 5 OF PROGRAM: FILE EDSCOND5.KBS

```
! Part 5 of EDS Condition Assessment Analyzer. Linked to file
! EDSCOND6.KBS

EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;
! Actions Block
ACTIONS
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     COLOR = 15
     LOADFACTS edsdata4
     DISPLAY "OK, We're ready to continue.  This program is in several
               parts"
     DISPLAY "due to memory constraints.  Press any key to begin the"
     DISPLAY "fifth part of this consultation, Outage Records Module,"
     DISPLAY "Overall System Module, and Summary.~"
     WCLOSE 1
     WOPEN 3,1,1,6,77,1
     WOPEN 4,8,1,13,36,3
     WOPEN 5,8,38,13,39,4
     ACTIVE 3
     COLOR = 15
     CLS
     ACTIVE 5
     COLOR = 15
     CLS
     DISPLAY "                        SUMMARY"
     DISPLAY "MODULE                   CI             RATING"
     DISPLAY "Substation         {5CI_Substation}       {9Sub_Rate}"
     DISPLAY "Cable Network      {5CI_Cable}       {9Dist_Rate}"
     DISPLAY "Transformers       {5CI_Transformers}       {9Pwr_Trans_Rate}"
     DISPLAY "Switchgear         {5CI_Switchgear}       {9Switchgear_Rate}"
     DISPLAY "Maint/Inspect      {5CI_Maint}       {9Maint_Rate}"
     DISPLAY "Diagnostic Tools {5CI_Tools}       {9Diag_Tools_Rate}"

! Actions Block for Power Outage Records Module
ACTIVE 4       !Change windows
COLOR = 0
CLS
DISPLAY "EXECUTING - Outage Records Module:

This module is designed to assess
data from your power outage
records.  The data will be used
to aid in evaluating the
condition of the electrical
distribution system based on
frequency, cause, and duration
```

```
of past power outages.
For an explanation of each
question, type / followed by 3."

     ACTIVE 3        !Change windows
     COLOR = 15
     CLS
     valuecior = 100
     FIND CIORF    ! Determine condition index for Outage Records
                   ! frequency
     FIND CIORC    ! Determine condition index for Outage Records
                   ! Cause
     FIND CIORD    ! Determine condition index for Outage Records
                   ! Duration/Extent

     CI_Outage = ((0.36*CIORF)+(0.39*CIORC)+(0.25*CIORD))

     FIND Outage_Rate

     ACTIVE 5
     COLOR = 15
     DISPLAY "Outage Records   {5CI_Outage}      {9Outage_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS

!Actions Block for System Summary

     ACTIVE 4        !Change windows
     COLOR = 0
     CLS
     DISPLAY "EXECUTING - Summary Module:

This module is designed to
Summarize all of the results
and calculate the OVERALL system
condition index, CI(EDS)."

     ACTIVE 3        !Change windows
     COLOR = 15
     CLS

!  Calculate the condition index for the key subsystems CI(Systems)

CI_Systems = ((0.33*CI_Substation)+(0.28*CI_Cable)
                   +(0.16*CI_Transformers)+(0.23*CI_Switchgear))

!  Calculate the condition index for key system factors CI(Factors)

CI_Factors = ((0.41*CI_Maint)+(0.32*CI_Tools)+(0.27*CI_Outage))
```

```
! Calculate the OVERALL SYSTEM condition index CI(EDS)

CI_EDS = ((0.67*CI_Systems)+(0.33*CI_Factors))

     FIND Overall_Rate

     ACTIVE 5
     COLOR = 0
     DISPLAY "OVERALL CI(EDS)   =  {7CI_EDS}"
     DISPLAY "OVERALL RATING   ={9Overall_Rate}"
     ACTIVE 3
     COLOR = 15
     CLS
     DISPLAY "Press any key to continue.~"
     CLS

     FIND Print      !  See if printout is desired

WHILETRUE Print = YES
THEN
DISPLAY "Please insert paper and ready printer.  Press any
key to continue.~"
PRINTON
     DISPLAY "                        SUMMARY"
     DISPLAY " "
     DISPLAY "     MODULE            CI            RATING"
     DISPLAY "     ______________________________________"
     DISPLAY "     Substation      {5CI_Substation}      {9Sub_Rate}"
     DISPLAY "     Cable Network    {5CI_Cable}      {9Dist_Rate}"
     DISPLAY "     Transformers {5CI_Transformers} {9Pwr_Trans_Rate}"
     DISPLAY "     Switchgear   {5CI_Switchgear}  {9Switchgear_Rate}"
     DISPLAY "     Maint/Inspect    {5CI_Maint}      {9Maint_Rate}"
     DISPLAY "     Diagnostic Tools {5CI_Tools}   {9Diag_Tools_Rate}"
     DISPLAY "     Outage Records   {5CI_Outage}      {9Outage_Rate}"
     DISPLAY "     ______________________________________"
     DISPLAY " "
     DISPLAY "     OVERALL CI(EDS)   =  {7CI_EDS}"
     DISPLAY "     OVERALL RATING   ={9Overall_Rate}"
CLS
Print = 1
END

! Actions Block for summary of critical components scoring poor

     FIND Summary   !  See if Summary is desired

WHILETRUE Summary = YES
THEN
SAVEFACTS EDSDATA5
CHAIN EDSCOND6
RESET Summary
END
```

```
WHILETRUE Summary = NO
THEN                    ! End program if summary is not requested
RESET Summary
CHAIN EXIT
END
;

! Rules Block for Outage Records Module

RULE CIORF
IF outages >= 0
     AND valuecior >= (5*outages)
THEN CIORF = (100 - (5*outages))
ELSE CIORF = 0
BECAUSE "The total number of power outages experienced (regardless
of cause) can be used to assess the condition of the system
in terms of how it handles outages.";

RULE CIORC
IF comp_outages >= 0
     AND valuecior >= (12*comp_outages)
THEN CIORC = (100 - (12*comp_outages))
ELSE CIORC = 0
BECAUSE "The number of power outages caused by component failure
can be used to determine the condition of the electrical
distribution system.";

RULE CIORD1
IF outages = 0
THEN CIORD = 100
BECAUSE "There were no power outages, therefore no duration.";

RULE CIORD2
IF duration <= 2
     OR extent <= 25
     AND cause = NO
THEN CIORD = 85

BECAUSE "Cause, duration, and extent are all factors affecting
the condition of the system.";

RULE CIORD3
IF duration <= 4
     OR extent <= 50
THEN CIORD = 70
BECAUSE "Cause, duration, and extent are all factors affecting
the condition of the system.";

RULE CIORD4
IF duration <= 8
     AND extent <= 75
THEN CIORD = 50
```

```
BECAUSE "Cause, duration, and extent are all factors affecting
the condition of the system.";

RULE CIORD5
IF duration > 8
     OR extent > 75
     AND cause = NO
THEN CIORD = 25
ELSE CIORD = 0
BECAUSE "Cause, duration, and extent are all factors affecting
the condition of the system.";

RULE Outage_Rating_Excellent
IF CI_Outage >= 90
THEN Outage_Rate = Excellent
BECAUSE "Maximum possible points for CI_Outage is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Outage_Rating_Good
IF  CI_Outage < 90
     AND CI_Outage >= 80
THEN Outage_Rate = Good
BECAUSE "Maximum possible points for CI_Outage is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";


RULE Outage_Rating_Fair_or_Poor
IF CI_Outage < 80
AND CI_Outage >= 60
THEN Outage_Rate = Fair
ELSE Outage_Rate = Poor
BECAUSE "Maximum possible points for CI_Outage is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

! Rules Block for Overall Module

RULE Overall_Rating_Excellent
IF CI_EDS >= 90
THEN Overall_Rate = Excellent
```

```
BECAUSE "Maximum possible points for CI_EDS is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Overall_Rating_Good
IF  CI_EDS < 90
     AND CI_EDS >= 80
THEN Overall_Rate = Good
BECAUSE "Maximum possible points for CI_EDS is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";

RULE Overall_Rating_Fair_or_Poor
IF CI_EDS < 80
AND CI_EDS >= 60
THEN Overall_Rate = Fair
ELSE Overall_Rate = Poor
BECAUSE "Maximum possible points for CI_EDS is 100.
Rating scale is:
      90 - 100    ==> Excellent
      80 -  89.99 ==> Good
      60 -  70.99 ==> Fair
       0  - 59.99 ==> Poor";


! Statements Block for Outage Records Module

ASK outages: "How many power outages has your base experienced during
the past 12 months?  Please count ALL outages regardless of cause.
";
RANGE outages:0,50;

ASK comp_outages: "How many power outages were the direct result of
component failure (i.e. high-voltage cable failure, transformer
failure, etc.)?  Count only outages affecting more than 10%
of the base.";
RANGE comp_outages:0,50;

ASK duration: "What was the duration, in hours, of the worst power
outage experienced by the base?  Consider worst in terms of
duration, extent, and mission criticalness of area affected
by outage.  Do not consider cause of outage.";
RANGE duration:0,240;
```

```
ASK extent: "What percentage of the base was affected by the worst
power outage experienced during the past 12 months?  Please enter
as a whole percentage (i.e. 33% is 33, on-fourth is 25, etc.).";
RANGE extent:0,100;

ASK cause: "Was the worst power outage experienced by the base in the
past 12 months the direct result of component failure?";
CHOICES cause:YES,NO;

ASK Print: "Would you like a printout of the results?";

ASK Summary: "Would you like a summary of the critical components and
critical system subfactors which have a condition index
below 70 (CI between 60 and 70 is considered fair)?";
CHOICES Print,Summary:YES,NO;
```

PART 6 OF PROGRAM: FILE EDSCOND6.KBS

```
! Part 6 of EDS Condition Assessment Analyzer, Summary Module.

EXECUTE;
RUNTIME;
BKCOLOR=1;
ENDOFF;

! Actions Block

ACTIONS
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     COLOR = 15
     LOADFACTS edsdata5
     DISPLAY "OK, We're ready to continue.  This program is in several
             parts"
     DISPLAY "due to memory constraints.  Press any key to begin the"
     DISPLAY "final part of this consultation, Summary.~"
     WCLOSE 1
     WOPEN 6,2,2,18,75,3
     ACTIVE 6
     COLOR = 0

WHILETRUE Print = 1
THEN
PRINTON
RESET Print
END

     DISPLAY " "
     DISPLAY "      The following critical components and/or critical
                    system subfactors
      received a condition index (CI) rating of 70 or lower.  These
      critical components and/or critical system subfactors should be
      considered for increased levels of maintenance and repair, when
      applicable, or for enhanced program development.
      "

WHILETRUE CISCB <= 70 THEN        ! The next 23 WHILETRUE Loops test
     DISPLAY "      Substation Circuit Breakers"     ! to see if CI
RESET CISCB                                          ! is less than 70
END                                                 ! for each component
                                                     ! or subfactor
WHILETRUE CISBS <= 70 THEN
     DISPLAY "      Substation Bypass Switches"
RESET CISBS
END

WHILETRUE CISPT <= 70 THEN
     DISPLAY "      Substation Primary Transformer(s)"
```

```
RESET CISPT
END

WHILETRUE CISR <= 70 THEN
     DISPLAY "      Substation Relays"
RESET CISR
END

WHILETRUE CIDCNC <= 70 THEN
     DISPLAY "      High-Voltage Conductors"
RESET CIDCNC
END

WHILETRUE CIDCNSS <= 70 THEN
     DISPLAY "      Distribution Cable Network Supporting Structure
            (Poles, manholes, conduit, etc.)"
RESET CIDCNSS
END

WHILETRUE CIDCNOC <= 70 THEN
     DISPLAY "      Distribution Cable Network Other Components
            (Switches, sectionalizers, reclosures, potheads, etc.)"
RESET CIDCNOC
END

WHILETRUE CIDCNT <= 70 THEN
     DISPLAY "      High-Voltage Cable Terminations"
RESET CIDCNT
END

WHILETRUE CI_Transformers <= 70 THEN
     DISPLAY "      Distribution Transformers"
RESET CI_Transformers
END

WHILETRUE CISS <= 70 THEN
     DISPLAY "      Switchgear Switch Mechanisms"
RESET CISS
END

WHILETRUE CISC <= 70 THEN
     DISPLAY "      Switchgear Cases"
RESET CISC
END


WHILETRUE CISSR <= 70 THEN
     DISPLAY "      Switchgear Relays"
RESET CISSR
END
```

```
WHILETRUE CIMIMP <= 70 THEN
     DISPLAY "      Maintenance and Inspection Plan"
RESET CIMIMP
END

WHILETRUE CIMITL <= 70 THEN
     DISPLAY "      Training Level"
RESET CIMITL
END

WHILETRUE CIMIME <= 70 THEN
     DISPLAY "      Manning and/or Experience"
RESET CIMIME
END

WHILETRUE CIMIPE <= 70 THEN
     DISPLAY "      Proper Tools and Equipment"
RESET CIMIPE
END

WHILETRUE CIDTCS <= 70 THEN
     DISPLAY "      Short Circuit Analysis/Coordination Study"
RESET CIDTCS
END

WHILETRUE CIDTDM <= 70 THEN
     DISPLAY "      Distribution System Drawings/Record and As-Built
Drawings"
RESET CIDTDM
END

WHILETRUE CIDTTS <= 70 THEN
     DISPLAY "      Thermographic Survey"
RESET CIDTTS
END

WHILETRUE CIDTMI <= 70 THEN
     DISPLAY "      Manufacturers' Instruction Manuals for Major
Equipment Items"
RESET CIDTMI
END


WHILETRUE CIORF <= 70 THEN
     DISPLAY "      Frequency of All Power Outages"
RESET CIORF
END

WHILETRUE CIORC <= 70 THEN
     DISPLAY "      Power Outages Caused By Component Failure"
RESET CIORC
```

```
END

WHILETRUE CIORD <= 70 THEN
     DISPLAY "      Duration and Extent of Power Outages"
RESET CIORD
END

PRINTOFF

     DISPLAY "

      Press any key to continue.~"

CLS

DISPLAY "                        Thanks for consulting the:

"
DISPLAY "                      Electrical Distribution  System
"
DISPLAY "                       Condition Assessment Analyzer"

DISPLAY "




      PRESS ANY KEY TO EXIT THIS PROGRAM~"
;
```

PART 7 OF PROGRAM: FILE EXIT.KBS

```
EXECUTE;
RUNTIME;
BKCOLOR=1;

ACTIONS
     COLOR = 0
     WOPEN 1,2,5,18,69,3
     ACTIVE 1
     DISPLAY " "
     DISPLAY " "
     DISPLAY "                    Thanks for consulting the"
     DISPLAY "                 Electrical Distribution System"
     DISPLAY "                 Condition Assessment Analyzer"
     DISPLAY " "
     DISPLAY "               (PRESS ANY KEY TO EXIT THE PROGRAM)~"
;
```

Appendix F: Database Update Program and Report

The following listing is a sample dBase III program which updates a selected database file to determine the overall condition index (CI) of each transformer in the distribution transformer network. The overall CI is based on the weighted average of individual component condition indices (each component was evaluated on a scale of 1 - 10, with 10 being the best). The overall condition index is then evaluated in one of four categories: excellent, good, fair, or poor. These categories are used by the expert system in Appendix E to determine the overall CI of the entire distribution transformer network. A sample database report for the transformer network is included following the update program.

Update Program:

```
* TRANSFOR.PRG
* Program to automatically update the CITOTAL (Overall
*   condition index) and CONDITION Fields in the
*   dBase III+ database file TRANSFOR.DBF. Updates
*   are based on weighted average of individual
*   rating fields (CIDTIM,CICASE,CIAGE,CILOAD,CIDTPD)

set echo on

* Select database
select 1
use TRANSFOR

* Carry out calculations

replace all CITOTAL with CIDTIM*0.26+CICASE*0.10+CIAGE*0.10
                                     +CILOAD*0.24+CIDTPD*0.30
replace all CONDITION with "Excellent" for CITOTAL >= 9.00
replace all CONDITION with "Good" for CITOTAL < 9.00
                                 .and. CITOTAL >= 8.00
replace all CONDITION with "Fair" for CITOTAL < 8.00
                                 .and. CITOTAL >= 6.00
replace all CONDITION with "Poor" for CITOTAL < 6.00
                                 .and. CITOTAL > 0.00
close database

set echo off
```

Sample Database Report:

08/11/91

Transformer Inspection Report

ID #	Component Condition: Insul-ation	Case	Age	Load	Protect Devices	Total Condition Index	Evaluation Rating	Transformer Rating
0001	9	8	7	9	9	8.70	Good	100 KVA
0002	8	8	6	9	5	7.14	Fair	150 KVA
0003	5	4	5	9	7	6.46	Fair	120 KVA
0004	10	9	9	9	9	9.26	Excellent	150 KVA
0005	5	7	7	7	7	6.48	Fair	600 KVA
0006	9	9	5	5	8	7.34	Fair	125 KVA
0007	8	8	9	8	7	7.80	Fair	200 KVA
0008	10	8	8	9	8	8.76	Good	100 KVA
0009	9	9	9	8	9	8.76	Good	200 KVA
0010	8	7	7	8	7	7.50	Fair	75 KVA
0011	8	8	8	7	8	7.76	Fair	200 KVA
0012	10	8	8	9	8	8.76	Good	150 KVA
0013	8	6	9	8	8	7.90	Fair	200 KVA
0014	8	9	7	7	8	7.76	Fair	75 KVA
0015	8	9	8	5	8	7.38	Fair	150 KVA
0016	9	9	10	8	8	8.56	Good	200 KVA
0017	8	8	9	8	6	7.50	Fair	125 KVA
0018	9	9	10	9	10	9.40	Excellent	125 KVA
0019	9	7	7	8	7	7.76	Fair	125 KVA
0020	8	9	10	9	10	9.14	Excellent	200 KVA
0021	5	7	8	5	5	5.50	Poor	125 KVA
0022	8	9	8	7	8	7.86	Fair	75 KVA
0023	10	10	9	8	9	9.12	Excellent	600 KVA
0024	8	9	8	8	9	8.40	Good	125 KVA
0025	9	8	8	9	7	8.20	Good	100 KVA
0026	6	6	5	7	5	5.84	Poor	125 KVA
0027	5	5	4	5	6	5.20	Poor	125 KVA
0028	5	4	5	9	8	6.76	Fair	75 KVA
0029	9	10	9	9	8	8.80	Good	125 KVA
0030	8	9	9	8	7	7.90	Fair	250 KVA
0031	9	8	8	9	9	8.80	Good	125 KVA
0032	7	9	6	9	9	8.18	Good	150 KVA
0033	9	8	8	8	8	8.26	Good	150 KVA
0034	9	5	7	5	5	6.24	Fair	125 KVA

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Vita

Captain David O. Paine was born in Texas City, Texas on 12 December 1958. After graduating from Midwest City High School in Midwest City, Oklahoma in 1977, he attended Oklahoma State University, from which he received the degree of Bachelor of Science in Electrical Engineering in July 1982. Upon graduation, he received a commission in the USAF through the ROTC program. Captain Paine began his active duty service in the 3245th Civil Engineering Squadron at Hanscom AFB, Massachusetts. During this assignment, he was project manager for the first "build-to-lease" program constructed at an Air Force Base in the United States. In December 1984, he was assigned to the 36th Civil Engineering Squadron at Bitburg AB, West Germany, where he developed an award winning energy conservation program. In March 1988, he was promoted to the position of Chief, Construction Management and was responsible for on-going construction projects valued at more than $140 million. In May 1989, he changed positions to Chief, Engineering and Technical Design where he managed a design program comprising 150 projects valued at $200 million. In June 1990, Captain Paine entered the Air Force Institute of Technology, School of Systems and Logistics, from which he earned a Master of Science degree in Engineering Management in September 1991. Upon graduation, he was assigned to the 2849th Civil Engineering Squadron, Hill AFB, Utah.

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Faced with rapidly decreasing budgets, the Air Force is in need of a method to objectively evaluate its aging utility infrastructure assets. This objective evaluation could be used to compare like facility infrastructure systems for identification of possible problem areas and prioritization of major repair projects.

This thesis developed a component model which can be used to objectively evaluate a typical electrical distribution system. The Delphi process was used to gather expert opinions regarding three areas: (1) the critical components which should be included in the model, (2) the relative importance of each selected critical component, and (3) the criteria used to evaluate each of the selected critical components. The model is used to assign a numerical rating ranging from 0 to 100 to each critical component. The condition indices for the critical components are then combined using a relative weighting scheme to arrive at the overall electrical distribution system condition index.

The component model was encoded into a computer based expert system shell to provide a smooth user interface and easy update capabilities. The resulting expert system determines component and system condition indices based on simple user input or database information (when available).

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